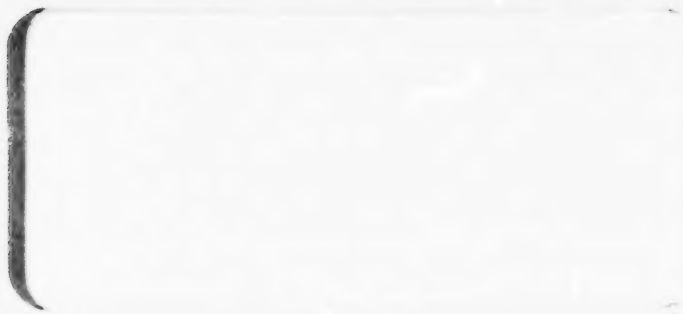

INCO

EXAMINATION OF THE 100% METHANOL ENGINE AS A POWER SOURCE FOR UNDERGROUND MINES

FINAL REPORT

BY

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Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources, Canada

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SUMMARY

This work was undertaken in response to a request for proposal issued by the Canadian Explosives Atmospheres Laboratory of CANMET. Methanol was identified as a potential fuel for use in heavy duty diesel engines as a substitute for diesel fuel, and as a means of achieving a cleaner exhaust from the engine. The KHD Deutz model 413 engine was identified as the most appropriate heavy duty diesel engine to use for a demonstration of methanol fuel in an underground diesel powered load-haul-dump (LHD) machine.

KHD Deutz modified a F8L413F engine to use methanol in their research laboratory in Cologne, West Germany. The principal modification consisted of using special glow plugs with an electronic control system to provide a continuous source of ignition for the methanol. For safety purposes, 7 percent isopentane was added to the methanol.

The experimental engine was operated briefly in Germany and then shipped to Ontario Research Foundation (ORF) where it was installed in an engine test cell. Emissions were obtained over simulated load cycles for the LHD machine. Unfortunately, the particulate emissions of the engine were abnormally high, roughly equivalent to that of a normal diesel engine. This was traced to lubricating oil consumption by the engine, and thus the engine had to be partially rebuilt (top end). Afterwards, the particulate emissions were one order of magnitude lower than that of a regular diesel engine, more in line with what would be expected of a methanol engine. The exhaust quality index for the methanol engine was 47 as compared to 219 for a typical diesel engine.

The engine was then installed in a five cubic yard LHD at Inco and application was made to the Ontario Ministry of Labour to operate the machine at the Little Stobie Mine. It took some time to resolve the safety issues, during which the machine operated briefly on the surface. It was then operated in the underground mine, with refuelling taking place on the surface. However, the aldehyde emissions of the engine were one order of magnitude higher than had been anticipated from the test results obtained at ORF. Therefore, the machine was returned to the surface where it continues to operate at the Clarabelle Open Pit with the engine on loan from CANMET.

The methanol engine performed quite satisfactorily with no major mechanical or ignition problems during the test period. The cause of the excessive aldehyde emissions could not be found due to lack of time and funds within this contract.

INTRODUCTION

This work was undertaken beginning in November 1984 in response to a request for proposal issued by the Canadian Explosives Atmospheres Laboratory of CANMET. Initially it was hoped to have the work completed by March 1986, but due to unforeseen problems, the work was not completed until March 1987.

The work was divided into four tasks consisting of (1) engine specification, procurement and run-in, (2) emissions evaluation, (3) adaptation to the load-haul-dump (LHD) machine, and (4) methanol engine demonstration.

A previous literature survey and technological assessment carried out with funding from the Ontario Ministry of Transportation and Communications identified the KHD Deutz engine as the best engine to use for this demonstration of methanol in an underground diesel powered machine. Thus an agreement was negotiated with KHD Deutz to provide an experimental engine at the same cost as a regular diesel engine in early 1985. Emissions tests were done at the Ontario Research Foundation (ORF) and the engine was installed in an Inco load-haul-dump (LHD) machine for evaluation by Inco mines department.

CONCLUSIONS

1) The KHD Deutz diesel engine operated reliably on the methanol fuel in normal mining operations. Power output was better than that of the same engine operated on diesel fuel. No problems were experienced in starting the engine, and there were no problems with the special equipment used to adapt the engine to methanol operation. Idle speed had to be raised from 650 RPM to 1000 RPM to eliminate a stalling problem when the operator first put his foot on the accelerator.

2) The methanol fuel was safely handled in the refuelling of the machine. There were no problems with the fuel system on the machine in underground operation. The only negative aspect of the refuelling system was the need to pump the fuel by hand in the surface refuelling facility while exposed to the winter weather. ($-25^{o}C$).

3) The emissions of oxides of nitrogen and carbon monoxide were well within acceptable limits in the mine. There was no problem with carbon dioxide levels in the mine air.

4) The emissions of soot by the methanol engine were one order of magnitude lower than that of the same type of engine operated on diesel fuel. The only visible particulates were when the engine was first started up. It would not be necessary to install a soot trap on a methanol engine to achieve a clean exhaust.

5) The aldehyde emissions of the engine were abnormally high. Extrapolating from the ORF test data, the aldehyde levels in the mine air were one order of magnitude higher than expected. This resulted in exceeding the TLV for aldehydes by a factor of three. The additional fuel consumption by the more powerful engine may have contributed to the unusually high aldehyde readings.

RECOMMENDATIONS

1) The engine requires troubleshooting to try to identify the cause of the abnormally high aldehydes. Possible causes to be checked out are: failure of the left hand catalytic converter, loss of exhaust heat between the manifold and the converter, defective injectors, valve lash adjustment, low operating temperature of the engine, overfuelling of the engine. Other factors would likely be discovered during the troubleshooting campaign.

2) Tests should be performed with other catalytic converters specifically designed for use with methanol fuel to try to improve the aldehyde emissions. These tests would be best done in a laboratory setting with equipment comparable to that used by ORF.

3) Additional work is needed to demonstrate the safety of methanol fuel in underground applications, particularly with respect to the handling of fuel spills and the fighting of fires. The Ontario Ministry of Labour approval was for a one-time application with refuelling to be done on the surface only. Approval for underground refuelling is expected to be denied by the Ministry.

DESCRIPTION OF WORK

TASK 1. Engine Specification, Procurement and Run-In.

Inco and ORF worked together to develop the specification for ordering the modified KHD engine, and to develop the terms for cooperation with KHD for this project.

A Deutz F8L 413F methanol engine was ordered in December 1984 from Klockner-Humboldt-Deutz (KHD), Cologne, West Germany. This engine was modified from a basic diesel engine to operate on methanol, by the KHD Research Center in Cologne. Figures 1 and 2 show the methanol engine. Modifications included the installation of an ignition source for the methanol fuel comprised of specially shielded glow plugs. Glow plug temperatures are between 950°C and 1050°C. Power to the glow plugs was varied relative to engine speed and load using an electronic controller. This consisted of a mother board and one daughter board for each glow plug. The revised version consists of a single board which would be supplied by KHD for any future work. The controller picks up engine RPM signals and exhaust gas temperature and modulates the power pulse to each glow plug accordingly.

Methanol fuel is injected into the combustion chamber via a specially designed injector. The injector is fitted with a shield (see Figure 4) to disperse the fuel and minimize direct impact on the glow plug. Fuel spray is directed into a bowl in the top of the piston. The fuel delivery was doubled relative to normal diesel volumes to take into account the lower energy content of methanol fuel (about half of diesel). Figure 3 shows the injection pump. A 24 volt electric fuel pump was used to deliver fuel to the Bosch P-type injection pump. KHD utilized the standard lubricating circuit for the injection pump. The circuit included a provision for vapourizing methanol entrained in the lubricating oil and delivering the vapourized methanol to the intake manifold.

The Deutz methanol engine was fitted with two (2) catalytic converters in the exhaust system (see Figure 6). These converters, coated with a precious metal catalyst, were used to oxidize carbon monoxide and hydrocarbon compounds.

The methanol engine was inspected at KHD's test facility in Cologne in April 1985 by representatives of INCO and ORF. KHD subjected the engine to a series of tests,

including engine recovery from a motoring condition. The INCO and ORF representatives recommended several minor modifications to the engine. These modifications included providing a fuel bleed line for priming the system, incorporating a fuel pressure gauge and shock mounting the electronic control unit. A list of spare parts was identified and KHD agreed to ship them with the engine. The engine performed well throughout the test trials. This included a 'cold' engine start at 5°C. Fuel used throughout the test trials at KHD was representative of that used in Germany's methanol demonstration program.

KHD provided additional support by training a KHD Canadian representative in the design and operation of the methanol engine. This proved valuable in latter stages of the program, when engine troubleshooting and repair were required.

The test engine, (Serial Number 6722061) was shipped to ORF on June 12, 1985. Preparations for testing the engine were made by installing a stainless steel underground storage tank for the methanol fuel. A fuel blend of 93% and 7% isopentane was used for all tests at ORF, as well as the field trials at INCO's mining operations. The addition of isopentane raised the vapour phase hydrocarbon concentration above the upper explosion limit.

Following engine installation at ORF, some minor problems were discovered with the glow plugs and electronic control unit. The glow plug elements were found to be loosening from the glow plug body. This problem was rectified by tack welding the element to the glow plug body. Electronic control unit problems were resolved by replacing appropriate printed circuit cards following consultation with KHD.

Tests conducted at ORF showed that engine performance, exhaust temperatures and fuel consumption (on an energy basis) values were comparable to those measured by KHD. Performance and fuel consumption were similar to the Deutz F8L 413FW diesel engine (indirect injection) normally used in underground mining operations. Following these tests, the engine was prepared for emissions testing, the results of which follow.

TASK 2. Methanol Engine Emissions Evaluation

2.1 Steady State Emissions Testing

Initial emissions tests were conducted over a 24 point load/speed matrix. These initial tests included measurement of undiluted concentrations of carbon dioxide (CO_2), carbon monoxide (CO), gaseous total hydrocarbon (THC), nitrogen oxide (NO) and nitrogen dioxide (NO_2). Concentrations were measured before and after the catalyst on one exhaust bank of the engine. The sampling system is shown in Figure 7.

Particulate tests were conducted at 75% of rated engine condition (2300 rpm/100 kW) with the total engine exhaust flowing into the dilution tunnel. The first series of tests showed that the particulate concentration averaged 21.1 mg/m^3. This level is abnormally high for a methanol engine. Additional tests were conducted with the methanol evaporator disconnected, resulting in a particulate concentration of 21.0 mg/m^3. A final series of tests was conducted with both the evaporator and crankcase vent disconnected. Results of these tests indicated a particulate loading of 18.9 mg/m^3. Based on the aforementioned test results, it appeared that the methanol engine was burning lubricating oil and hence producing high particulate emissions.

Partial disassembly of the engine revealed significant ash deposits in the combustion chamber (Figure 8). These deposits also covered the injector tip and holes in the glow plug shield (Figure 9). The backs of some intake valves were covered with lubricating oil and most of the cylinder liners were glazed. Exhaust valve faces were covered with ash (Figure 5) and seats were significantly worn, resulting in valve recession. Based on these observations, it was evident that the engine required a partial rebuild to correct the oil consumption problem.

KHD agreed to rebuild the engine to correct the oil problem. The following steps were taken by KHD:

- replaced two (2) pistons;
- installed hardened exhaust valve seats;

- installed intake valve seals;*
- replaced all piston rings;
- cleaned all piston ring grooves;
- de-glazed all cylinder liners.

Because of those problems, it was necessary to repeat the emissions test work at ORF. Inco therefore applied to CANMET for a contract amendment in November 1985 to add $22,000 to the project budget and extend the delivery date from March 1986 to August 1986.

The rebuilt engine was operated under a break-in schedule following repairs made by KHD. A subsequent check of particulate emissions at the same load/speed condition showed that the particulate concentration was less than 2 mg/m^3. This result confirmed that the high particulate levels were associated with the combustion of lubricating oil. The emission test runs were then repeated.

Gaseous concentrations for the thirteen point load/speed test matrix are given in Table 1. Concentrations of CO_2, CO, THC (as CH_4 and corrected for oxygenates), NO and NO_2 are given in this table. Plots of concentration versus engine load at each of the three speed conditions (2300, 2000 and 1500 rpm) are given in Figures 10 through 27. Test results show that the catalytic converters were effective in lowering CO and THC concentrations under all engine operating conditions. The high engine CO concentrations (4247 ppm) found during 'lug-down' condition (peak torque) were lowered to less than 150 ppm. It is noteworthy that the catalysts also appeared to act as a reducing catalyst by converting NO_2 to NO under all but one engine operating condition. Conversion efficiency of NO_2 to NO was greatest at the low load engine conditions.

*It is believed that this was the major problem, leading to the high particulate emissions.

2.2 Emissions Testing Over Simulated LHD Cycles

Gaseous and particulate emissions were measured using ORF's emissions test facility (see Figure 28). With the use of a computer controlled system, the engine was subjected to simulated load-haul-dump (LHD) operation. Two test cycles were used; the MTU cycle (59% load factor) and the more heavily loaded MTU MOD 5 cycle (63% load factor). Plots of engine speed and load for the MTU MOD 5 LHD cycle are given in Figures 29 and 30, respectively.

The engine was delivered from KHD with solenoid valves and a control system to shut off the fuel flow to one bank of the engine, thereby simulating motoring the engine. This feature was removed by ORF for the tests.

Particulate samples for the Ames bioassay were collected over the MTU MOD 5 cycle, using a dilution tube apparatus (illustrated in Figure 31). The dilution tube incorporates a 20 cm x 25 cm Teflon coated filter followed by a polyurethane foam filter. Aldehyde samples were collected over the MTU MOD 5 cycle, using two (2) different methods; an impinger method, shown in Figure 32, and a cartridge method. In both methods, the aldehydes are converted by hydrazone derivatives in the presence of 2,4 dinitrophenylhydrazone (2,4-DNPH).

The average methanol engine conditions during the MTU and MTU MOD 5 cycles are given as follows:

Engine Parameter	MTU Cycle	MTU MOD 5 Cycle
Engine Speed (rpm)	2164	2095
Engine Torque (N.m.)	306	402
Fuel Consumption (g/s)	11.8	13.6
Brake Specific Fuel Consumption (g/kW.h)	611	554
Left pre-catalyst exhaust temperature (^{o}C)	319	384

Engine Parameter	MTU Cycle	MTU MOD 5 Cycle
Left post-catalyst exhaust temperature (^{o}C)	323	390
Right pre-catalyst exhaust temperature (^{o}C)	325	390
Right post-catalyst exhaust temperature (^{o}C)	330	392
Intake air temperature (^{o}C)	38	38
Cooling air temperature (^{o}C)	24	28
Oil temperature (^{o}C)	83	92
Cylinder head temperature (^{o}C)	79	93
Fuel (methanol) temperature (^{o}C)	40	45
Exhaust backpressure (kPa)	1.02	1.10
Oil pressure (kPa)	461	429
Fuel pressure (kPa)	672	662

The above data (oil temperature and cylinder head temperature) show that the engine was operating at relatively cool temperatures. Normal oil temperature for the diesel version of this engine is approximately 110^{o}C to 120^{o}C.

The average post-catalyst gaseous pollutant concentrations for both test cycles are summarized as follows:

Pollutant	MTU Cycle	MTU MOD 5 Cycle
Carbon Dioxide (%)	4.95	6.15
Carbon Monoxide (ppm)	77	68

The average post-catalyst gaseous pollutant concentrations for both test cycles are summarized as follows:

Pollutant	MTU Cycle	MTU MOD 5 Cycle
Total Hydrocarbons (ppm as CH_4)	34	18
Nitric Oxide (ppm)	341	458
Nitrogen Dioxide (ppm)	26	59
Nitrogen Oxides (ppm)	367	517

Three consecutive particulate tests were carried out for each of the MTU and MTU MOD 5 cycles. Particulate test results are summarized in Table 2. The total particulate concentrations averaged 1.50 mg/m^3 for the MTU cycle and 1.74 mg/m^3 for the MTU MOD 5 cycle. The soluble fraction accounted for about 34% of the total particulate material for both cycles. Particulate concentrations for the diesel version of this engine operating over the same cycles is between 60 mg/m^3 and 80 mg/m^3.

The results of the aldehyde tests are shown in Tables 3 and 4 for the impinger and cartridge methods, respectively. Total aldehyde levels found using the impinger collection method are about 60% lower than that found using the cartridge method. Formaldehyde accounts for the majority of the total carbonyl compounds measured. It is expected that the catalysts were effective in reducing the aldehyde concentrations emitted by the methanol engine. However no measurements of aldehyde concentration in the raw exhaust were taken. It was beyond the scope of this contract to develop a catalytic converter specifically designed for a methanol engine.

Results of subjecting the soluble particulate fraction to the Ames Bioassay are given in Table 5. The specific activity (revertants/ g extract) without metabolic activitation is 3.3, whereas with metabolic activation, the specific activity was found to be 2.1. These results translate to an exhaust revertant concentration

(revertants per cubic metre exhaust) of 13,261 and 20,840 for assay conditions with and without metabolic activation, respectively.

The particulate results from the high volume sampling apparatus showed a concentration of 7.34 mg/m^3; a factor of 4.2 higher than the result observed for the dilution tunnel. It is apparent that the material collected on the polyurethane foam filters accounted for the discrepancy.

Table 6 compares exhaust emissions from the methanol engine to its diesel-powered counterpart (without catalytic converters). Appropriate results were entered into the Exhaust Quality Index (EQI) in an effort to assess the emissions improvement with methanol fuel. The EQI formula is presented as follows:

$$EQI = \frac{CO}{TLV_{CO}} + \frac{NO}{TLV_{NO}} + \frac{RCD}{RCD_{limit}} + 1.5\left[\frac{SO_2}{\text{"}SO_{2_{limit}}\text{"}} + \frac{RCD}{RCD_{limit}}\right]$$

$$+ 1.2^{*}\left[\frac{NO_2}{TLV_{NO_2}} + \frac{RCD}{RCD_{limit}}\right]$$

where TLV is the threshold limit value and RCD is respirable combustible dust. The resultant EQI values are 219 for the diesel engine (untreated exhaust) and 47 for the methanol engine.

DESCRIPTION OF WORK

TASK 3. Methanol Engine Adaptation to a LHD Machine

A standard Wagner 5 cubic yard machine (number 582) which was being rebuilt was modified to accept the methanol engine in place of the regular 8 cylinder KHD Deutz series 413FW engine. It was necessary to change the motor mounts of the machine to accept the 413F type engine mounts. A fuel capacity of 326 litres was necessary since the energy content per litre of the alcohol is half that of diesel fuel. Therefore, two stainless steel fuel reservoirs were fitted to the machine with one way check valves and flame traps. All of the fuel lines were changed to stainless steel/Teflon, including all of the fittings. The 326 litre tank was only sufficient for five hours of operation in the mine, and this was the largest tank which could be readily fitted to the machine.

The entire electrical system of the machine had to be changed to 24 volt operation since the special purpose control system for the glow plugs of the methanol engine was designed by KHD to operate on 24 volts. This involved changing the instrument gauges, the lights, hydraulic solenoids, relays, alternator, indicating lamps, and the batteries.

To distinguish the machine from other machines in the Inco fleet, it was painted orange with prominent labels indicating that it was to use methanol fuel only. Special instructions were painted onto the machine about fuel usage, 24 volt operation and technical assistance from Mines Research in the event of machine problems.

The special electronic control package for the glow plugs was installed on top of number two fuel reservoir of the machine, with suitable environmental protection against moisture, dust and vibration.

Special mounts were fabricated for the tachometer, the control unit, the master electrical disconnect switch and a carbon monoxide monitor. The throttle and start fuel system were changed from manual to pneumatic. Covers and brackets were built for the new fuel pump, filters and batteries. New catalytic converters were fitted to the machine. A new bell housing also had to be fitted to the engine since the original one had been damaged when the engine was shipped to Inco.

Extensive meetings were held with the Inco safety committee and the Ministry of Labour regarding the use of this special fuel underground where it would normally not be permitted. The duration of these meetings and the delays in awaiting approval was a major source of delay in the field demonstration. CANMET authorized a contract amendment to extend the delivery date of the results until March 1987 and to add a further $5300 to the overall project budget on account of the extra costs that the delay incurred.

For the field demonstration, the fuel was a blend of 93% methanol and 7% isopentane, the latter being added to raise the vapour phase hydrocarbon concentration above the upper explosion limit. As well, in the event of a fuel fire, the isopentane would give the flame a colour whereas a pure methanol flame is virtually colourless. In addition, a yellow dye was purchased from Morton Thiokol (Yellow 101) and added to the fuel at a level of approximately 20 parts per million. The purpose of this dye was to give the fuel a distinctive colour in the event some is spilled since it was colourless.

Because of the safety consideration, refuelling was done on the surface using 45 gallon drums of fuel and a hand operated pump. Fire extinguishers were provided at the refuelling station. In addition, the machine itself was fitted with an automatic fire extinguisher system using remote sensors to trip the extinguishers.

Photographs of the machine with all of the installed modifications are given in figures 33, 34 and 35. For all practical purposes, it looks the same as any other LHD machine except for the labels and colour. The fuel with the dye added is shown in Figure 36.

TASK 4. Methanol Engine Demonstration

All of the modifications were completed on machine number 582 on March 31st, 1986, and the machine was then parked at the central repair shops while awaiting an operating permit from the Ontario Ministry of Labour. During this period, the machine was used for miscellaneous jobs such as snow removal and removal of garbage on the surface.

Letters were sent to the Ontario Ministry of Labour by the manager of the Frood Stobie complex on April 4 and April 15, 1986. On April 30th, the Ministry replied with a detailed letter requesting further data on 12 major points before the machine could be used underground. It was estimated that a further $12,000 or more would have to be spent to answer the points raised in this letter. It was agreed finally that a meeting could be held with Ministry officials to verbally answer these questions rather than develop a detailed report to answer the twelve points. This meeting was held in Sudbury on October 1st, 1986, after which Ministry officials inspected the test machine. The Ministry then gave Inco permission for a 500 hour underground test of the machine.

While awaiting this permission, the machine was tested on the surface for approximately 10.2 hours in total. On June 27th, smoke was noted from the right hand exhaust system. It was used to muck slag for several hours and there was some smell of methanol in the exhaust. The starting fuel linkage had to be repaired and the battery had to be changed. The electrical system was checked over. On July 2nd, the machine was parked again for the Inco summer shutdown. On August 21st, it was started again and it started at once after being shutdown for this period. Blue-black smoke was noted from both banks. After the engine was warmed up, there was still some smell in the exhaust. The stall speed was too low and was adjusted by venting the fuel system.

On October 1st, the machine was operated as a demonstration for the Ministry of Labour officials. There was still some smoke on the right hand bank. On December 8th, the machine was delivered to the Little Stobie Mine and the operators were given the necessary training for fuelling and operation of the machine. The supervisor and the mechanics were also trained. During this period, the machine operated for an additional 15 hours to bring the total machine time up to 25.7 hours.

On December 9th, the machine was inspected by the Ontario Ministry of Labour while it operated for 5 hours underground. The operating temperature of the engine seemed to be too low since the cooling fan did not at times cut in and out. On December 10th, the machine operated for only half a shift since there was a stong smell when it was operated in some locations in the mine. On December 11th, the cooling blower shroud was removed, the machine was refuelled and then driven underground for a ventilation test. The following results were noted while the machine was mucking:

1st test - after 3 buckets - 0 ppm of aldehydes

2nd test - after 2 buckets - 2 ppm of aldehydes

3rd test - after 2 buckets - 3 ppm of aldehydes

4th test - after 2 buckets - 3 ppm of aldehydes

The TLV for aldehydes is 1 ppm. The machine was therefore brought back to the surface to investigate the cause of the high aldehyde readings. The U.S. representative of KHD Deutz was contacted to obtain the schematic of the control system for the blower solenoid.

On December 16th, the schematic drawings of the blower control solenoid were received from KHD Deutz, Atlanta. Some faulty connections were found and modifications were made on December 18th, including removing and cleaning the glow plug shields. On December 22nd, the machine was checked out and returned to the 1500 level for ventilation tests while the machine was mucking. The tests were taken approximately 20 feet downwind of the machine while it was in the muchpile. The following readings were taken in the general atmosphere of the mine:

8:55 A.M.	Aldehyde	= 3.0 P.P.M.	(TLV = 1.0 ppm)
(Nitrogen Dioxide)	NO_2	= 1.0 P.P.M.	(TLV = 3.0 ppm)
(Nitrus Fumes)	NO	= 8.0 P.P.M.	(TLV = 25.0 ppm)
(Carbon Monoxide)	CO	= 18.0 P.P.M.	(TLV = 50.0 ppm)
(Carbon Dioxide)	CO_2	= Normal	

General Atmosphere Readings (Cont'd)

2-	9:05 A.M.	Aldehyde	=	3.0+	ppm
		NO2	=	0.6	ppm
		NOx	=	6.0	ppm
		CO	=	21.0	ppm
3-	9:20 A.M.	Aldehyde	=	3.0	ppm
		NO2	=	0.6	ppm
		NOx	=	21.0	ppm
		CO	=	8.0	ppm

CO Test at Scrubbers:

Right hand scrubber	=	100	ppm
Left hand scrubber	=	400	ppm

Over a period of approximately 45 minutes, 11 buckets were taken from the draw point to the ore pass, and the ventilation readings were taken.

On December 23rd, the machine was tested on the 1050 level but the aldehyde level remained above 3 ppm and the operators continued to complain of the smell.

On January 7th, the machine was transferred to the Clarabelle Open Pit garage to continue to work on the aldehyde problem. By this time, it had accumulated 47.4 hours, of which 37 hours had been spent in the underground mine. On January 14th, 1987, a new operator and supervisor were trained the operation and refuelling of the machine. The machine was then used on the surface to load ore onto the continous loader at the Clarabelle Open Pit mine. On January 21st, after 20 hours of operation, Inco ran out of methanol/pentane blend and an order was placed for an additional 20 drums of methanol and 2 of pentane. It then ran for a further 32 hours to a total of 99.4 hours ending on January 30th at the Clarabelle Open Pit. When a mechanic becomes available, further work will be done on the machine to try to decrease the aldehyde output. In the meantime. it will continue to be used on day shift at the open pit.

DISCUSSION OF RESULTS

At the conclusion of the contract, a loan agreement was concluded with CANMET so that Inco could retain the engine until March 31st, 1988 for further testing at Inco's expense. Until the aldehyde problem can be solved, this testing will continue at the Clarabelle Open Pit.

The field demonstration did however establish that the engine worked reliably over the actual load cycle of the LHD machine with no major mechanical or electrical problems during the 120 hour test (as of March 11th). Operators were pleased with the power output of the engine and load response. The only negative comments were with respect to the need to refuel the machine outside during the winter using a hand pump, and that the fuel capacity was found to be sufficient for only five hours of operation. Fuel consumption averaged 38 litres per hour. Because of the need to return up the ramp for refuelling, it is necessary to leave a reasonable amount of fuel in the tanks so that the fuel pump does not suck in air.

The carbon monoxide level from the right hand exhaust was recorded as 100 ppm as compared to 68 ppm by ORF for the MTU MOD 5 cycle. This is relatively good agreement since the field instrument would not be as accurate as the laboratory equipment at ORF. However, for the left hand exhaust, the carbon monoxide level was recorded as 400 ppm in the field test. This may indicate that the catalytic converter for the left hand exhaust is not working properly, or that there is a major combustion problem with the left hand side of the engine.

In the mine atmosphere measurements, the oxides of nitrogen were within acceptable limits, being typically about one third of that permitted by the regulations. The ratio of nitric oxide to nitrogen dioxide in the MTU MOD 5 cycle is about 7.7 for the ORF test. In two of the three spot checks by Inco in the mine, the ratio was 8 and 10. Some additional work could be done to improve the emissions of oxides of nitrogen if necessary, but there does not seem to be a problem since the measured values are well within the TLV's.

The major emission problem is the aldehyde level which is triple the permitted TLV, and in fact, was a major source of complaint in the operation underground. All

operators commented on the smell of the machine. Using the cartridge method for sample collection, ORF measured aldehyde concentrations of about 17 ppm in the exhaust after the catalytic converters. In the field test, Inco measured about 3 ppm in the mine air. In comparing the nitrogen oxides measured on the MTU MOD 5 cycle (517 ppm) with the average of nitrogen oxides measured in the mine air (7 ppm), the dilution of the exhaust by mine air apppears to be about 73. The mining ventilation system is designed to provide 125 CFM of air per horsepower, which calculates out to 24375 CFM for the 190 HP machine. The actual exhaust flow from a Deutz 413 engine at rated speed of 2095 RPM is 397 CFM (volumetric efficiency of 85 per cent). Thus, the air in the mine should be diluted by a factor of 24375/397, or 61, whereas the apparent dilution from the nitrogen oxides measurements is 73. It would be expected that the mine would be over-ventilated since the engine is not always running at full load (typical load factor about 63 percent), and there is a tendency to provide more air since there are some areas where there is an air distribution problem.

In the laboratory tests, ORF measured a value of 17 ppm for aldehydes by the cartridge method. Taking a dilution factor of 73, therefore, the expected value of aldehydes in the field test would be 17/73 or 0.2 ppm, whereas values of 3.0 ppm were recorded. Since the nitrogen oxides in the mine air were about what was expected, it is apparent that the aldehydes are abnormally high. Measurements of aldehydes could not be directly taken at the exhaust for a direct comparison with the ORF measurements.

One cause of the high aldehydes could be the poor performance of the left hand catalytic converter since the carbon monoxide levels were so high. There had been problems at ORF with the converters overheating in some of the runs, and new converters had to be used at Inco. The converter manufacturer had to replace the converters used by ORF. Another cause of high aldehydes could be poor valve adjustment on the engine. After the engine had been rebuilt, the valves were adjusted before it was returned in-service, but no in service adjustments were made, although it is generally necessary to do so after a top engine overhaul. A bad injector on the left hand bank of the engine could also explain the poor emission readings. The electronic control system would detect a bad glow plug, but there is no easy way to detect a poorly performing injector.

temperature of the engine. Engine oil temperature was typically about 80 to 90°C for the engine operating on alcohol fuel. In normal diesel operation the engine oil temperature ranges from 105°C to 120°C. It would be expected that the cooler operation on methanol fuel could lead to combustion problems which in turn could cause the high aldehyde emissions. Efforts to raise the operating temperature by repairing the blower controls were not successful.

It is planned to assign a mechanic and an engineer to the engine for trouble-shooting to try to track down the problem of the excessive aldehydes, despite being beyond the scope of the present contract since emission optimization was not the major objective.

The major objective of demonstrating the operation of a mining machine on alcohol fuel underground was achieved, although the running time underground had to be cut short because of the excessive aldehyde emissions and complaints from the operators about the smell of the exhaust.

TABLE 1

Gaseous Emissions Concentrations
Steady State Testing.

Engine Speed RPM	Engine Load %	Location Relative To Catalysts	CO_2 %	CO ppm	THC ppm	NO ppm	NO_2 ppm	NO_x ppm
2300	100	Before	7.60	333	206	523	153	676
		After	7.76	18	68	529	132	661
	75	Before	5.69	287	266	438	140	578
		After	5.80	23	76	433	135	568
	50	Before	4.51	403	219	305	130	435
		After	4.52	43	72	330	68	398
	25	Before	3.25	695	371	147	119	266
		After	3.29	86	152	210	39	249
2000	100	Before	8.27	693	192	492	149	641
		After	8.28	7	62	517	93	610
	75	Before	5.12	412	315	304	127	431
		After	5.21	35	92	342	94	436
	50	Before	4.43	506	353	244	124	368
		After	4.50	58	120	297	66	363
	25	Before	3.07	748	642	102	120	222
		After	3.13	119	313	167	41	208
1500	100	Before	8.76	4247	166	388	141	529
		After	9.44	148	88	524	64	588
	75	Before	6.43	415	203	402	108	510
		After	6.97	10	74	416	121	537
	50	Before	4.56	538	240	228	121	349
		After	4.78	26	72	292	69	361
	25	Before	3.08	642	444	102	123	225
		After	3.17	72	214	188	35	223
Idle	50	Before	2.89	325	251	186	115	301
		After	2.89	27	166	258	31	289

TABLE 2
Exhaust Particulate Test Result

Particulate Fraction	Units	MTU Cycle				MTU MOD 5 Cycle			
		1	2	3	Avg.	1	2	3	Avg.
Insoluble	g/h	0.40	0.33	0.33	0.35	0.40	0.26	0.53	0.40
Soluble	g/h	0.66	0.72	0.72	0.70	0.66	0.98	0.59	0.74
Total	g/h	1.05	1.05	1.05	1.05	1.06	1.25	1.12	1.14
Insoluble	g/kW.h	0.005	0.005	0.005	0.005	0.004	0.003	0.006	0.004
Soluble	g/kW.h	0.009	0.010	0.010	0.010	0.007	0.010	0.006	0.008
Total	g/kW.h	0.015	0.014	0.014	0.014	0.011	0.013	0.012	0.012
Insoluble	g/kg Fuel	0.009	0.008	0.008	0.008	0.008	0.005	0.011	0.008
Soluble	g/kg Fuel	0.015	0.017	0.017	0.016	0.013	0.020	0.012	0.015
Total	g/kg Fuel	0.025	0.024	0.024	0.024	0.021	0.025	0.022	0.023
Insoluble	mg/m^3	0.56	0.47	0.47	0.50	0.60	0.40	0.80	0.60
Soluble	mg/m^3	0.94	1.03	1.03	1.00	1.01	1.50	0.90	1.14
Total	mg/m^3	1.51	1.50	1.50	1.50	1.61	1.90	1.70	1.74
Insoluble	%	37.5	31.3	31.2	33.3	37.5	21.1	47.1	34.5
Soluble	%	62.7	68.7	68.8	66.7	62.5	78.9	52.9	65.5

TABLE 3
ALDEHYDE CONCENTRATIONS
IMPINGER METHOD

Aldehyde Compound	Test 1	Test 2	Test 3	Average
Formaldehyde				
ug/m^3	4910.61	4026.18	4054.49	
ppm	3.93	3.22	3.25	3.47
Acetaldehyde				
ug/m^3	306.06	677.48	670.77	
ppm	0.17	0.37	0.37	0.30
Acetone				
ug/m^3	490.80	786.65	666.99	
ppm	0.20	0.33	0.28	0.27
Crotonaldehyde				
ug/m^3	557.17	558.83	778.97	
ppm	0.19	0.19	0.27	0.22
MEK & Iso-But				
ug/m^3	3555.71	6466.05	3703.57	
ppm	1.19	1.15	1.23	1.19
Benzaldehyde				
ug/m^3	17.77	18.26	16.76	
ppm	0.004	0.004	0.004	<0.005
Hexanaldehyde				
ug/m^3	0.00	0.00	0.00	
ppm	0.00	0.00	0.00	
			Total	5.45 ppm

TABLE 4
ALDEHYDE CONCENTRATIONS
CARTRIDGE METHOD

Aldehyde Compound	Test 1		Test 2		Test 3		Average
	First	Backup	First	Backup	First	Backup	
Formaldehyde							
ug/m^3	16739.027	1225.21	22005.66	413.33	21286.60	386.03	
ppm	13.40	0.98	17.62	0.33	17.04	0.31	
	14.40		17.90		17.30		16.53
Acetaldehyde							
ug/m^3	144.17	697.89	40.34	169.77	255.43	498.85	
ppm	0.08	0.38	0.02	0.09	0.14	0.27	
	.40		0.11		0.41		0.31
Acetone							
ug/m^3	23.83	167.66	33.35	351.05	24.52	272.59	
ppm	0.01	0.07	0.01	0.15	0.01	0.11	
	0.08		0.16		0.12		0.12
Crotonaldehyde							
ug/m^3	0.00	289.27	0.00	0.00	11.32	0.00	
ppm	0.00	0.10	0.00	0.00	.00	0.00	0.00
MEK & Iso-But							
ug/m^3	0.00	0.00	0.00	0.00	0.00	0.00	
ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Benzaldehyde							
ug/m^3	0.00	0.00	0.00	0.00	0.00	0.00	
ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hexanaldehyde							
ug/m^3	0.00	0.00	0.00	0.00	0.00	0.00	
ppm	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Total		16.96

TABLE 5

RESULTS OF AMES BIOASSAY
SALMONELLA TESTER STRAIN TA-98

	Concentration ug/plate	S-9 MIX	Histidine Revertants			Mean +/-	Std.	Net Rev.
	500	-	461	431	434	442	17	417
	300	-	472	391	455	439	43	414
	250	-	406	380	326	371	41	345
	200	-	368	358	373	366	8	341
	150	-	379	394	386	386	8	361
*	100	-	333	333	333	333	0	308
*	50	-	156	185	160	167	16	142
*	10	-	35	27	53	38	13	13
	Negative Control	-	21	30	26	25	25	25	3	
	Historical Value	-						30		
	Positive Control	-			616	663	658	646	25.8	
	Historical Value	-						700		
	Compound	2 Nitrofluorene			2 ug/plate					
	Specific Activity							3.3		
	500	+			721	753	835	770	59	743
	300	+			579	544	503	542	38	515
	250	+			470	469	523	487	31	460
*	200	+			339	585	428	451	125	424
*	150	+			384	361	330	358	27	313
*	100	+			241	220	249	237	15	210
*	50	+			111	126	133	123	11	96
*	10	+			44	48	53	48	5	21
	Negative Control	+	40	22	19	33	21	27	9	
	Historical Value	+						25		
	Positive Control	+			1350	960	1178	1163	195	
	Historical Value	+						1597		
	Compound	2 Aminoanthracene			1 ug/plate					
	Specific Activity								2.1	

*Concentrations used to calculate specific activity.

TABLE 6

COMPARISON OF UNTREATED DIESEL EXHAUST EMISSIONS TO EMISSIONS FROM THE METHANOL ENGINE.

Variable	Diesel	Methanol
Engine Speed (rpm)	2123	2113
Engine Torque (Nm)	435	431
Fuel CBSFC (g/kW.h)	280	277
Carbon Dioxide (%)	7.5	6.1
Carbon Monoxide (ppm)	209	68
Total Hydrocarbons (ppm as C_1)	125	18
Oxides of Nitrogen (ppm)	670	517
Nitric Oxide (ppm)	630	458
Nitrogen Dioxide (ppm)	40	59
Total Particulate (mg/m^3)	75	1.74
Insoluble Particulate (mg/m^3)	18	0.60
Soluble Particulate (mg/m^3)	57	1.14
Aldehydes (ppm)	13	15
Ames Mutagenicity (rev/m^3)	39,000	20,840
Sulphur Oxides (ppm)	47	0

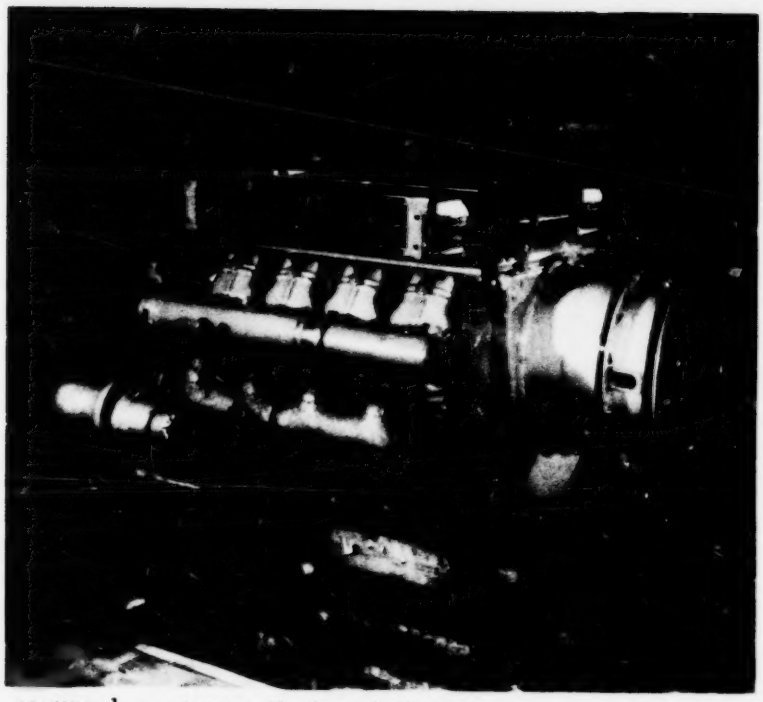


FIGURE 1 : Deutz Methanol Engine (Side View).

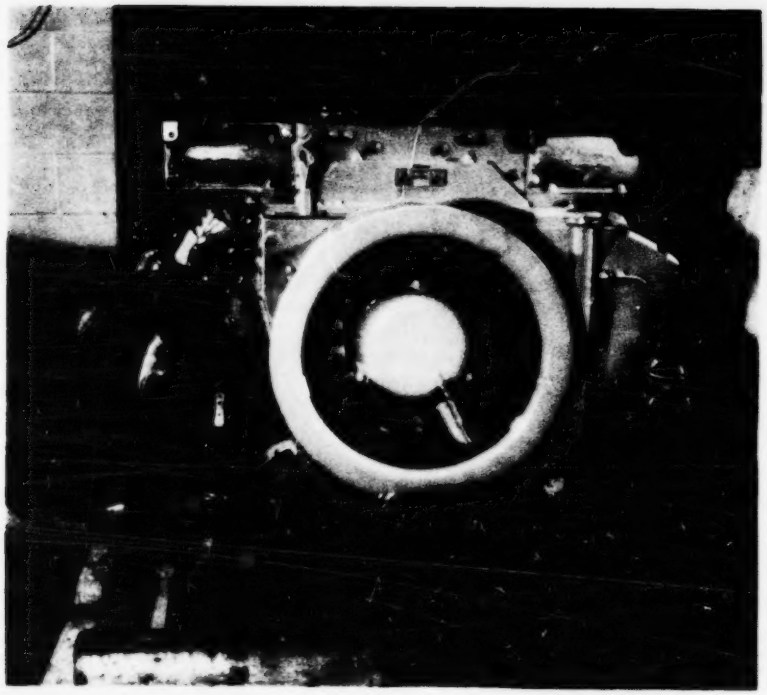


FIGURE 2 : Deutz Methanol Engine (Front View).

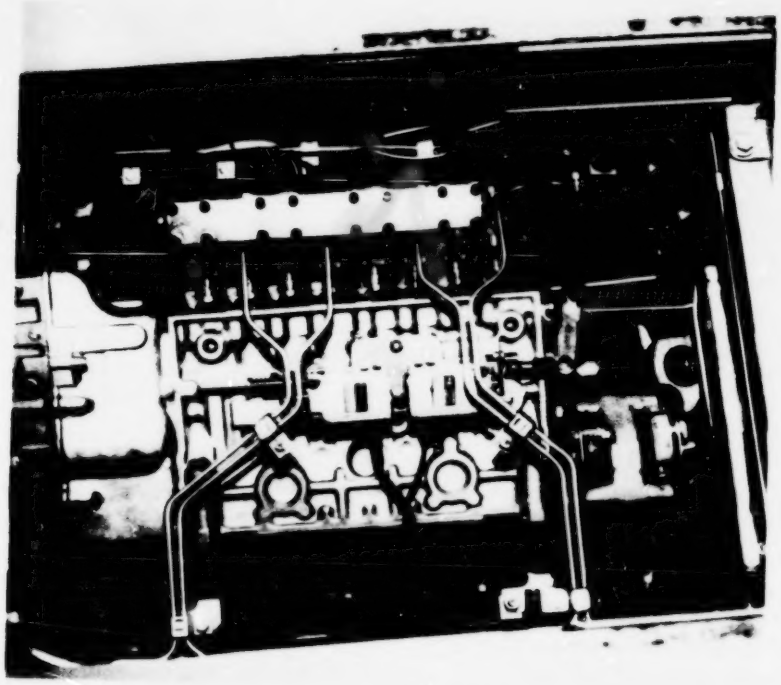


FIGURE 3: Methanol Engine Injection Pump (Showing shut-off solenoids).

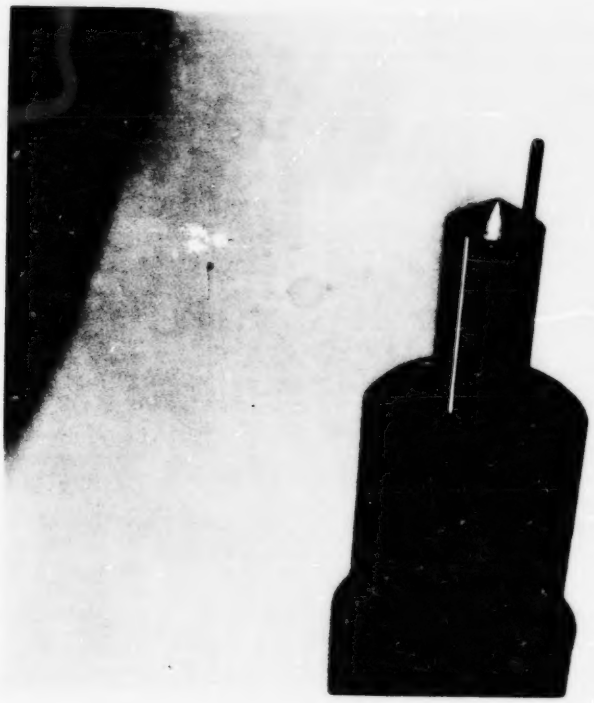


FIGURE 4: Injector Tip. (Showing metal rod).

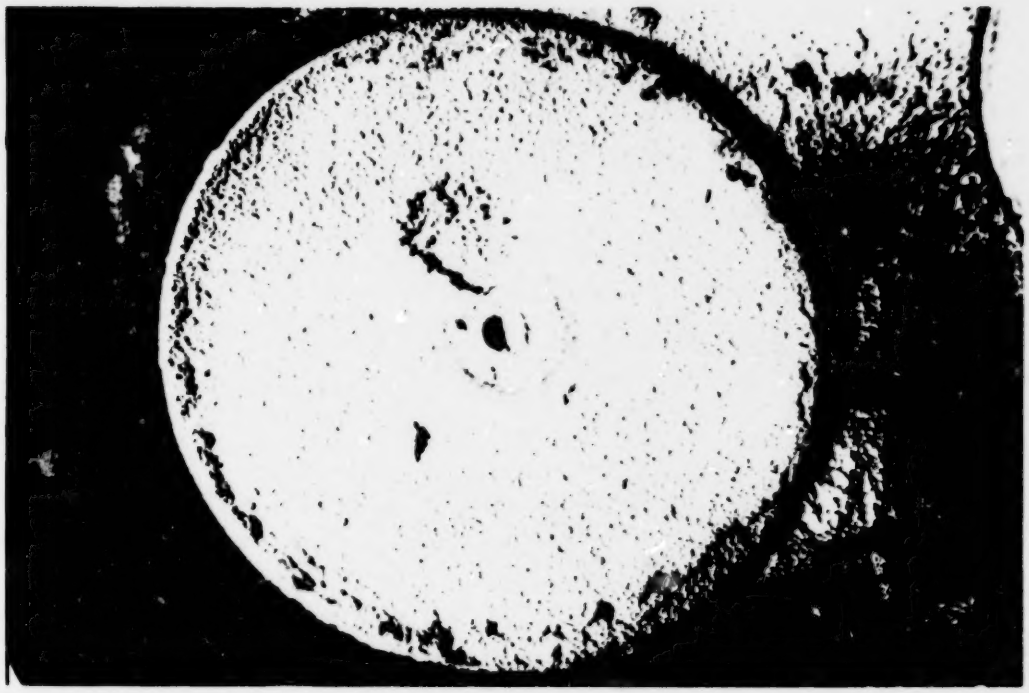


FIGURE 5 : Deposits on Valve Face.

FIGURE 6 : Catalytic Converter (without end cones).

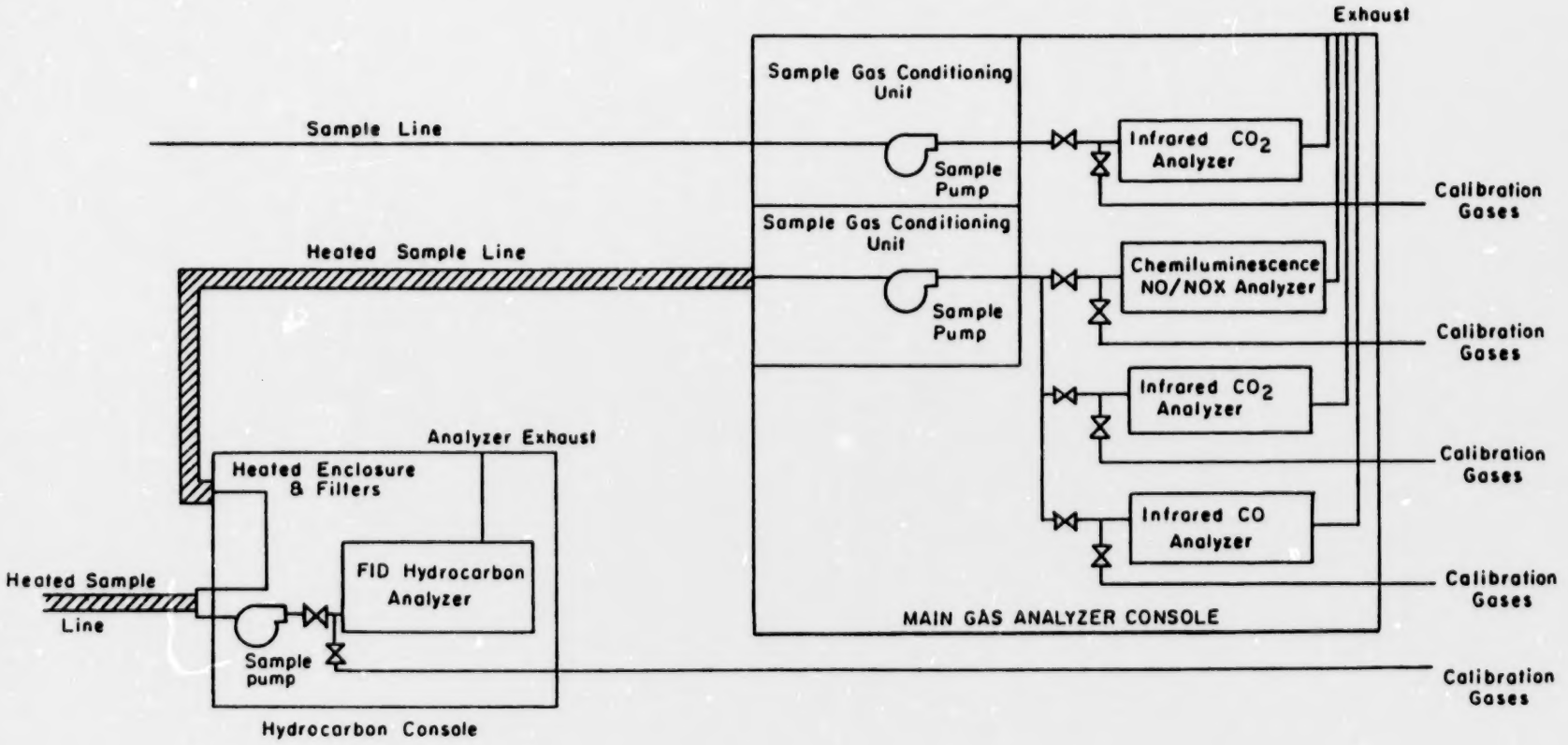


FIGURE 7 FLOW DIAGRAM FOR EXHAUST GAS SAMPLING

9 :

8 :

FIGURE 10

KHD METHANOL ENGINE

2300 RPM—%CO2 VS %LOAD

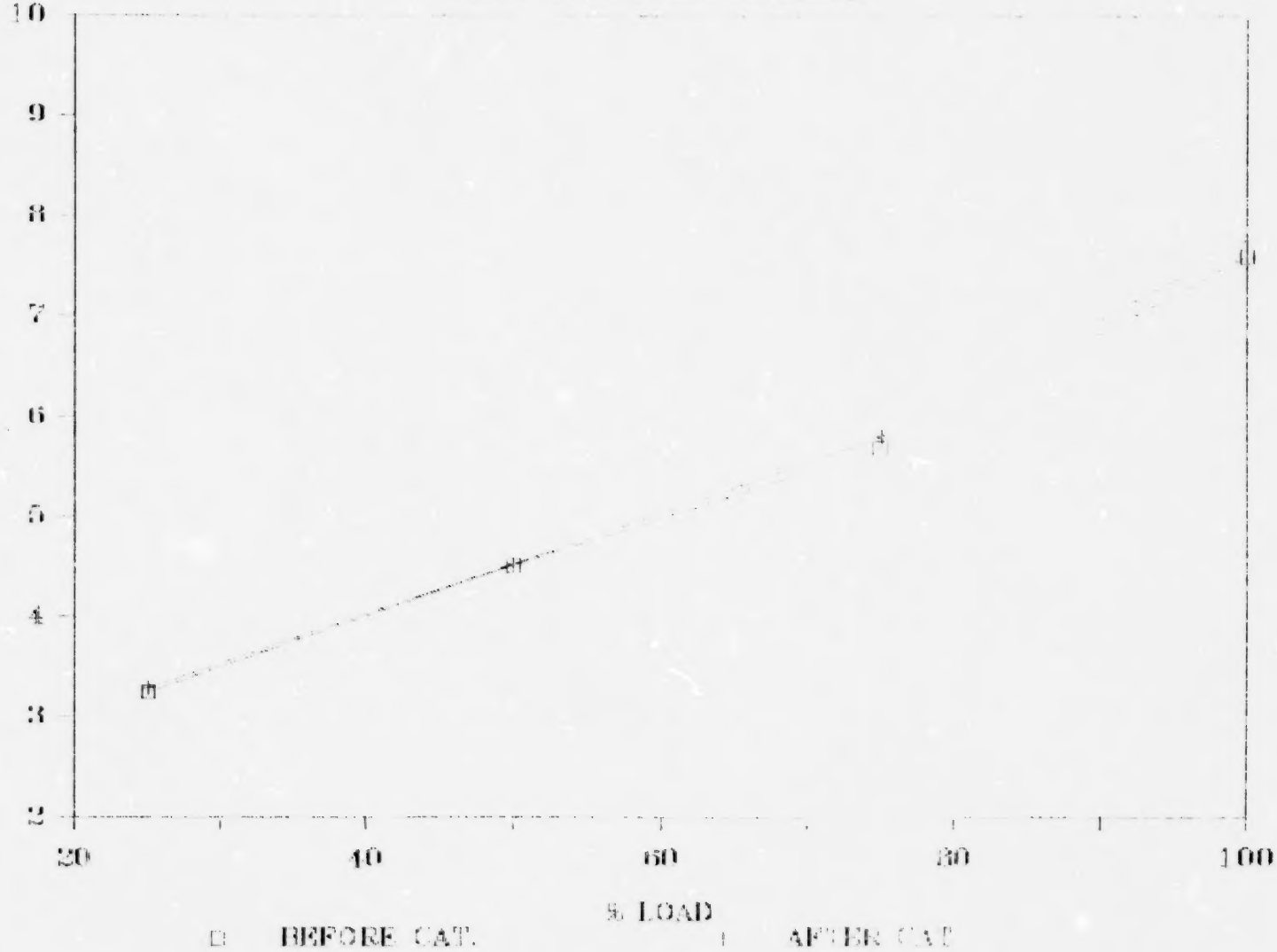


FIGURE 11

KHD METHANOL ENGINE

2300 RPM—THC AS CH4 (PPM) VS %LOAD

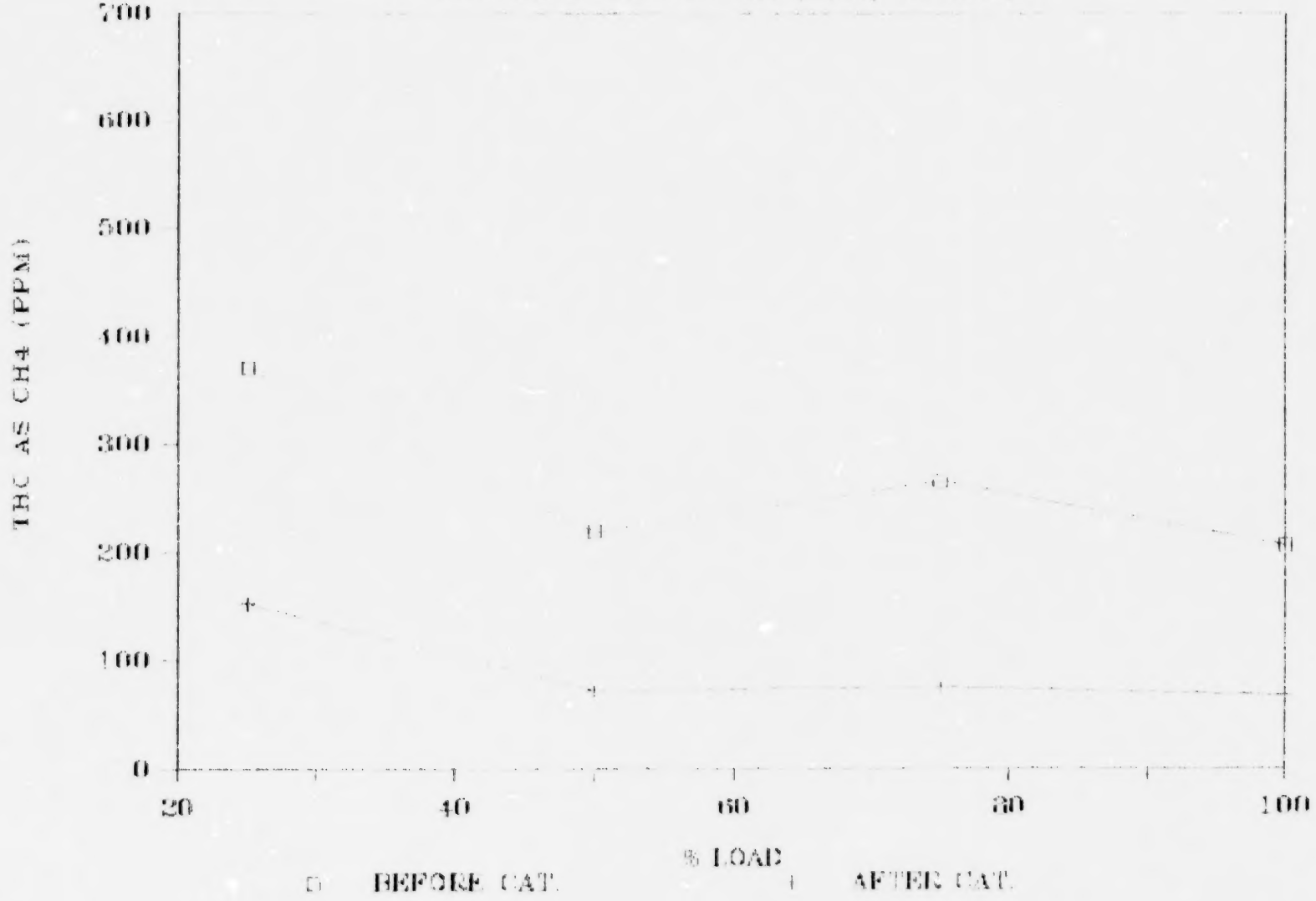


FIGURE 12

KHD METHANOL ENGINE

2300 RPM–CO(PPM) VS %LOAD

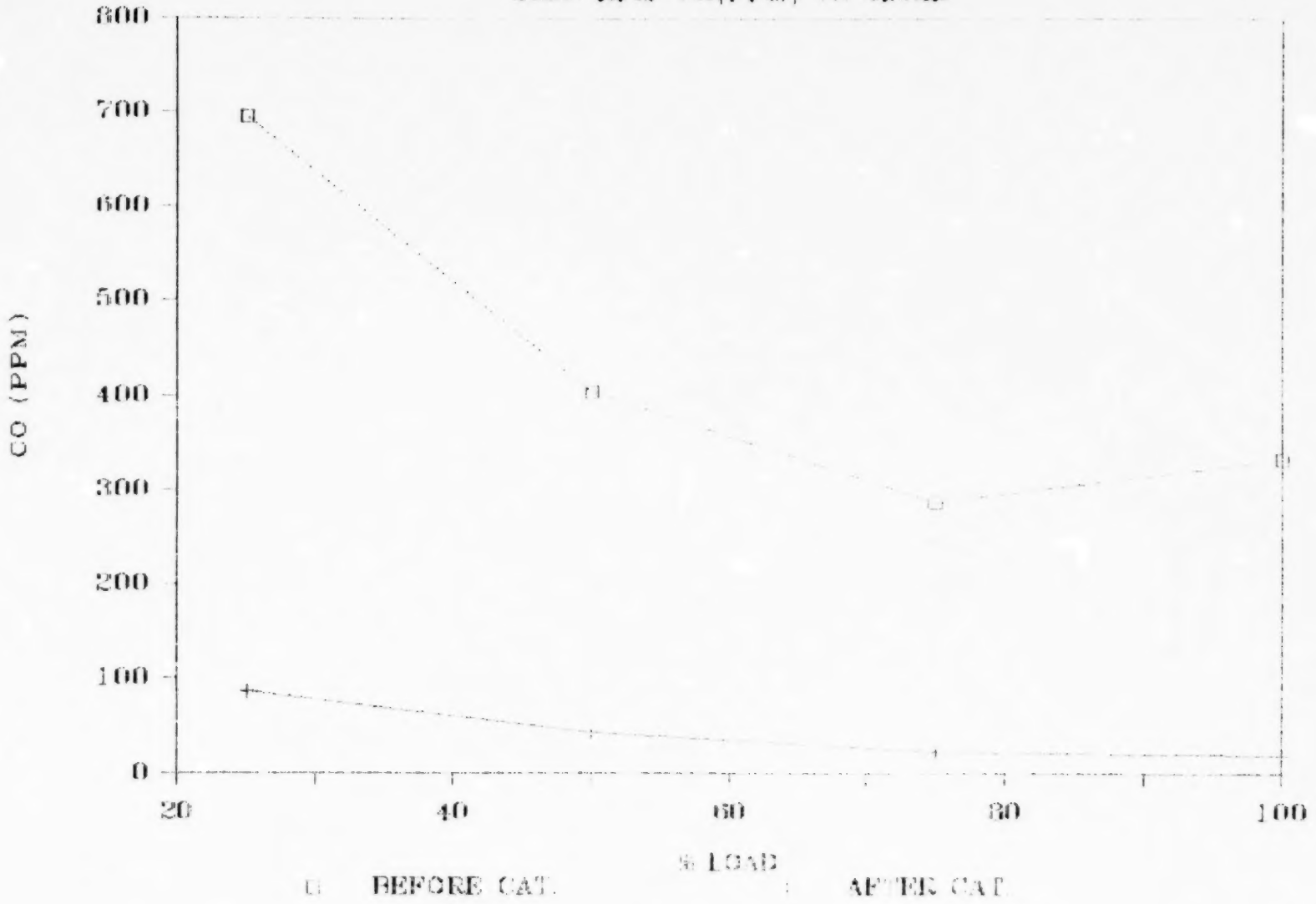


FIGURE 13

KHD METHANOL ENGINE

2300 RPM – NOX (PPM) VS %LOAD

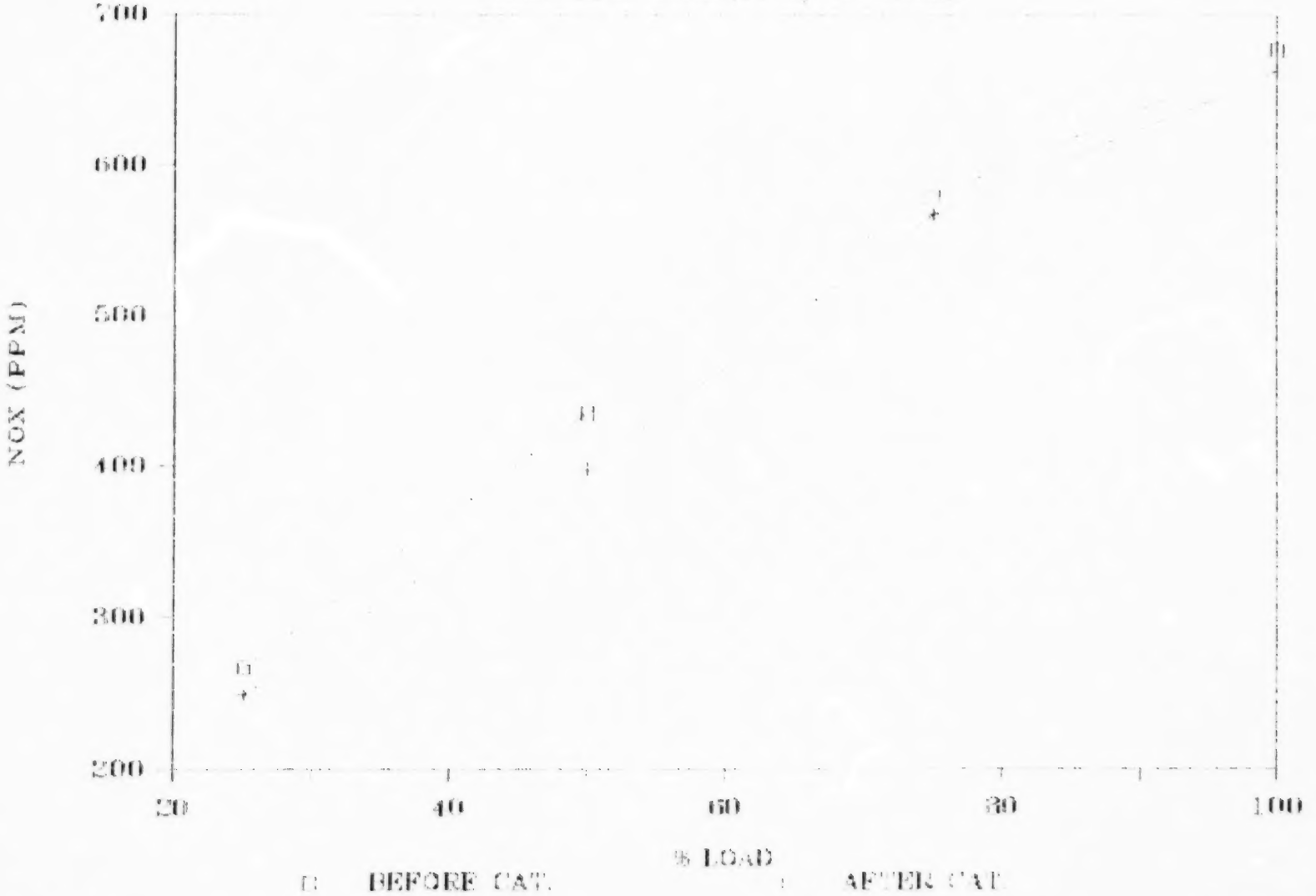


FIGURE 14

KHD METHANOL ENGINE

2300 RPM--NO (PPM) VS %LOAD

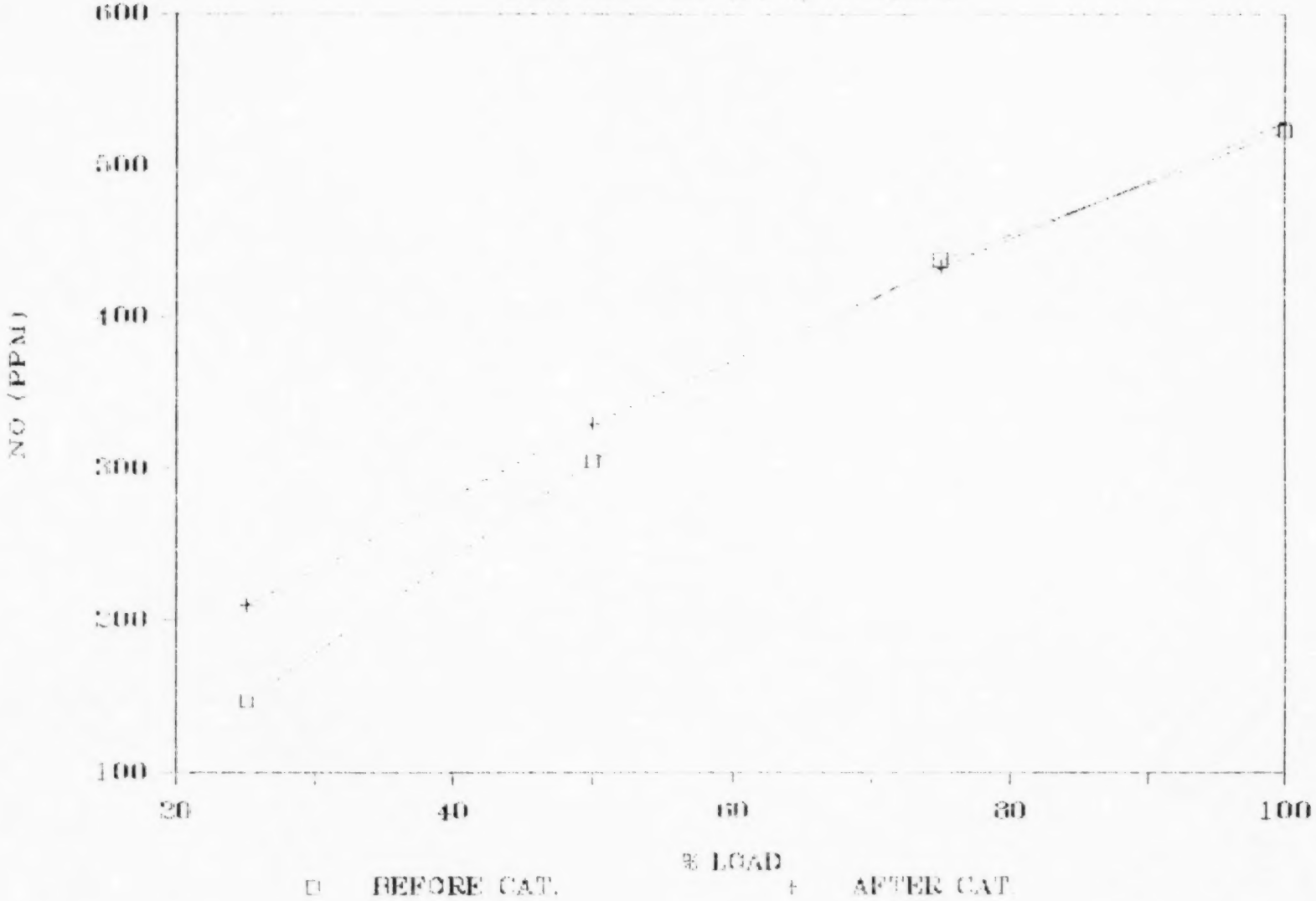


FIGURE 15

KHD METHANOL ENGINE

2300 RPM – NO2 (PPM) VS %LOAD

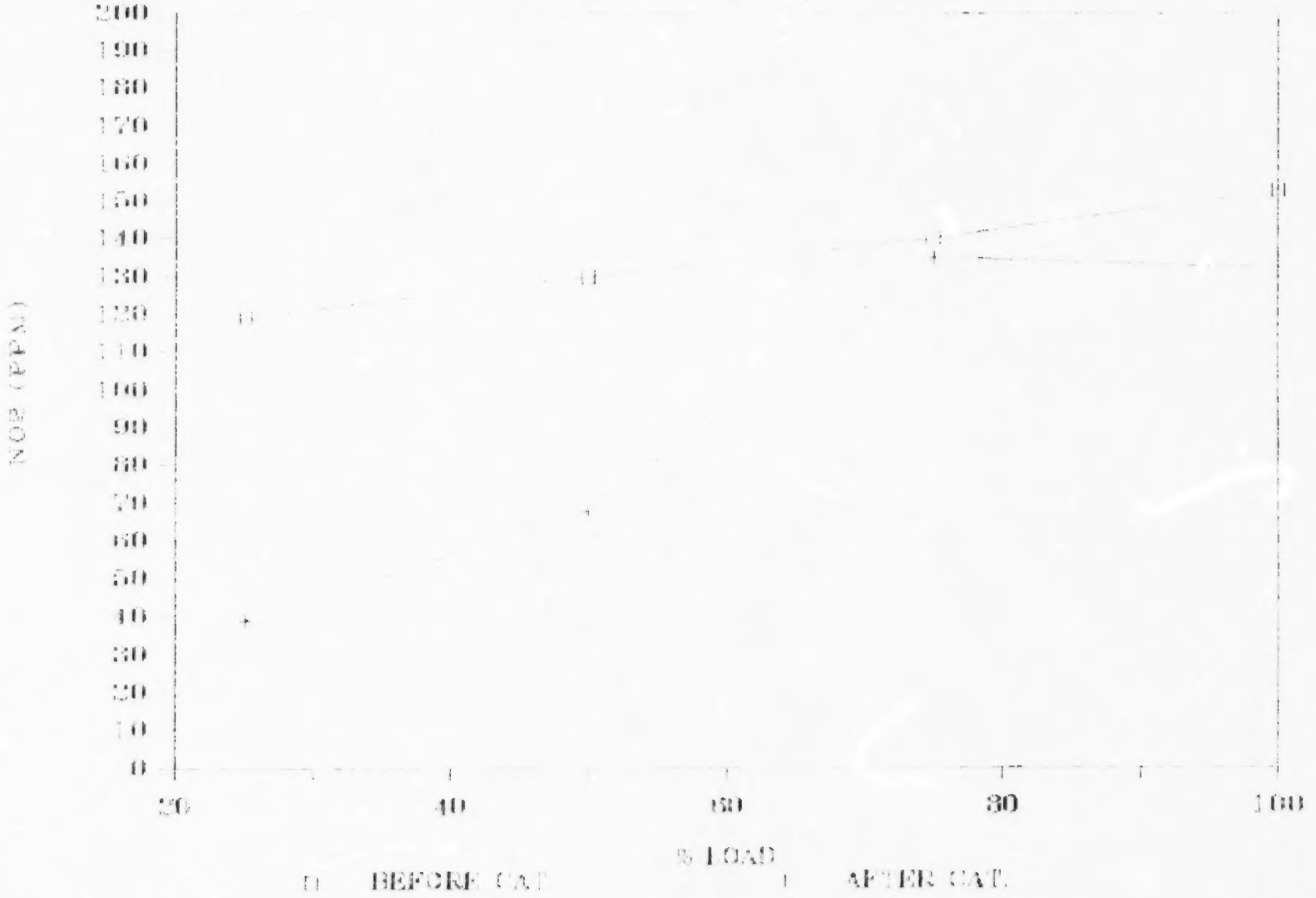


FIGURE 16

KHD METHANOL ENGINE

2000 RPM - % CO2 VS %LOAD

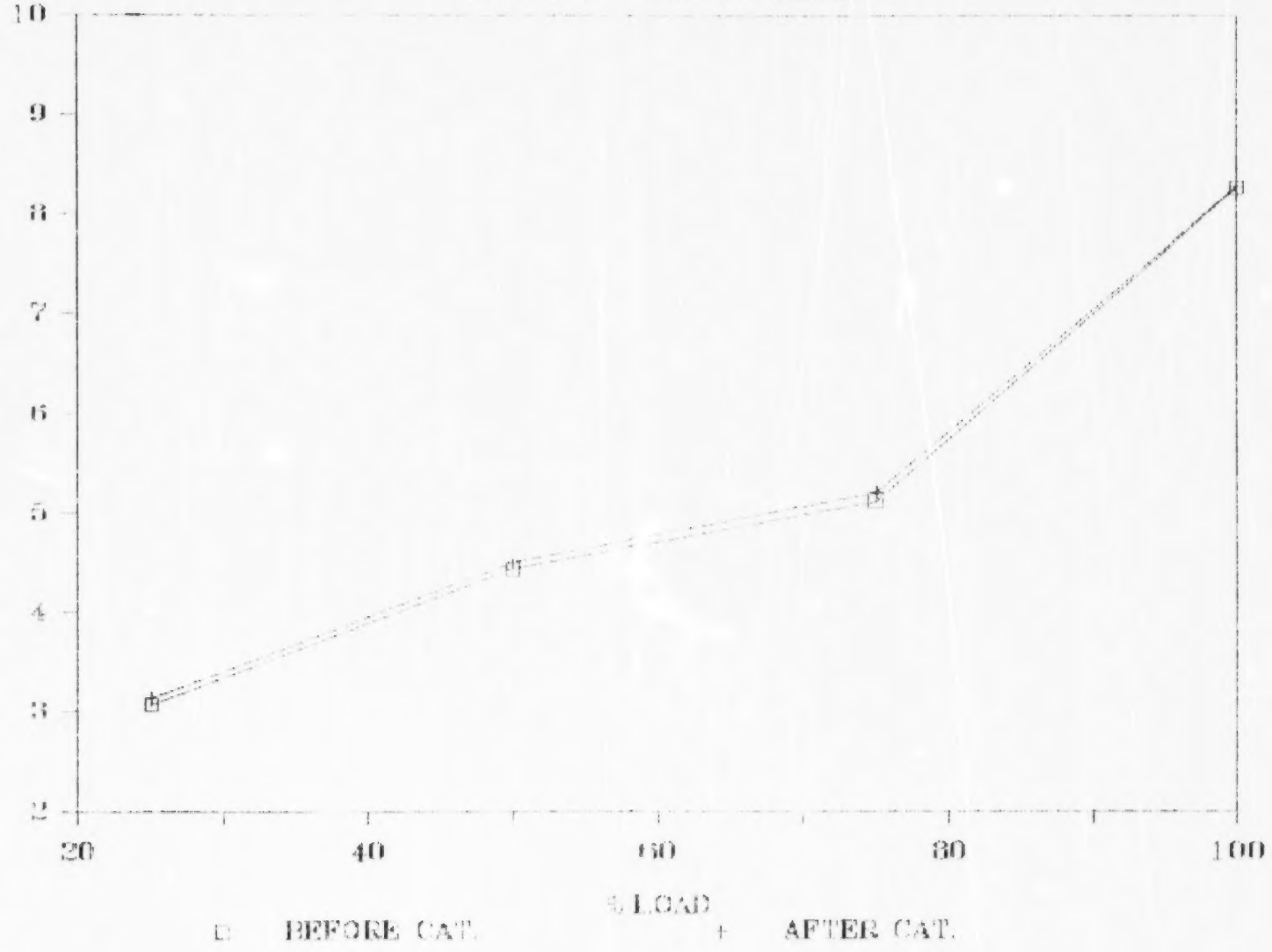


FIGURE 17

KHD METHANOL ENGINE

2000 RPM—THC AS CH_4 (PPM) VS %LOAD

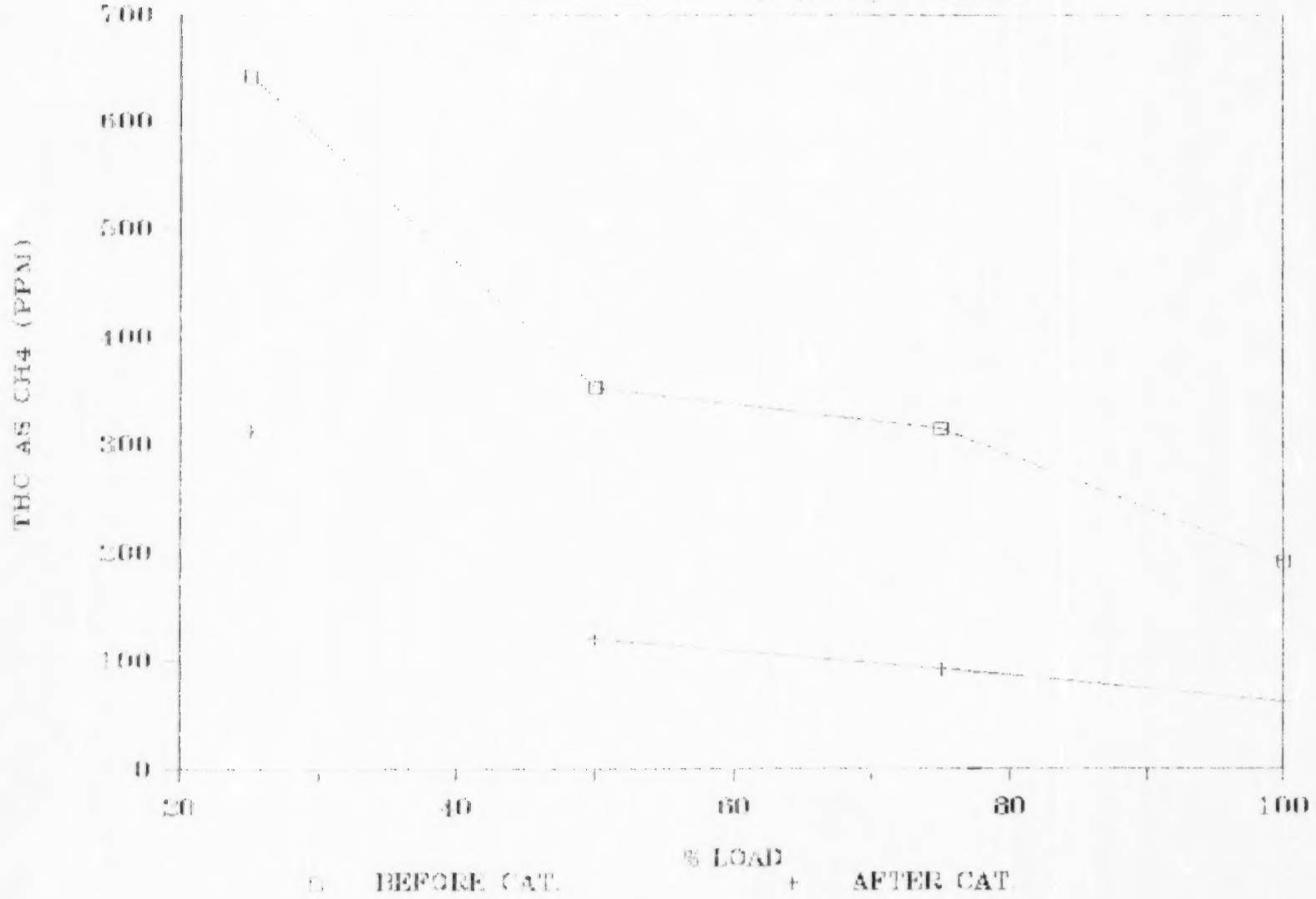


FIGURE 18

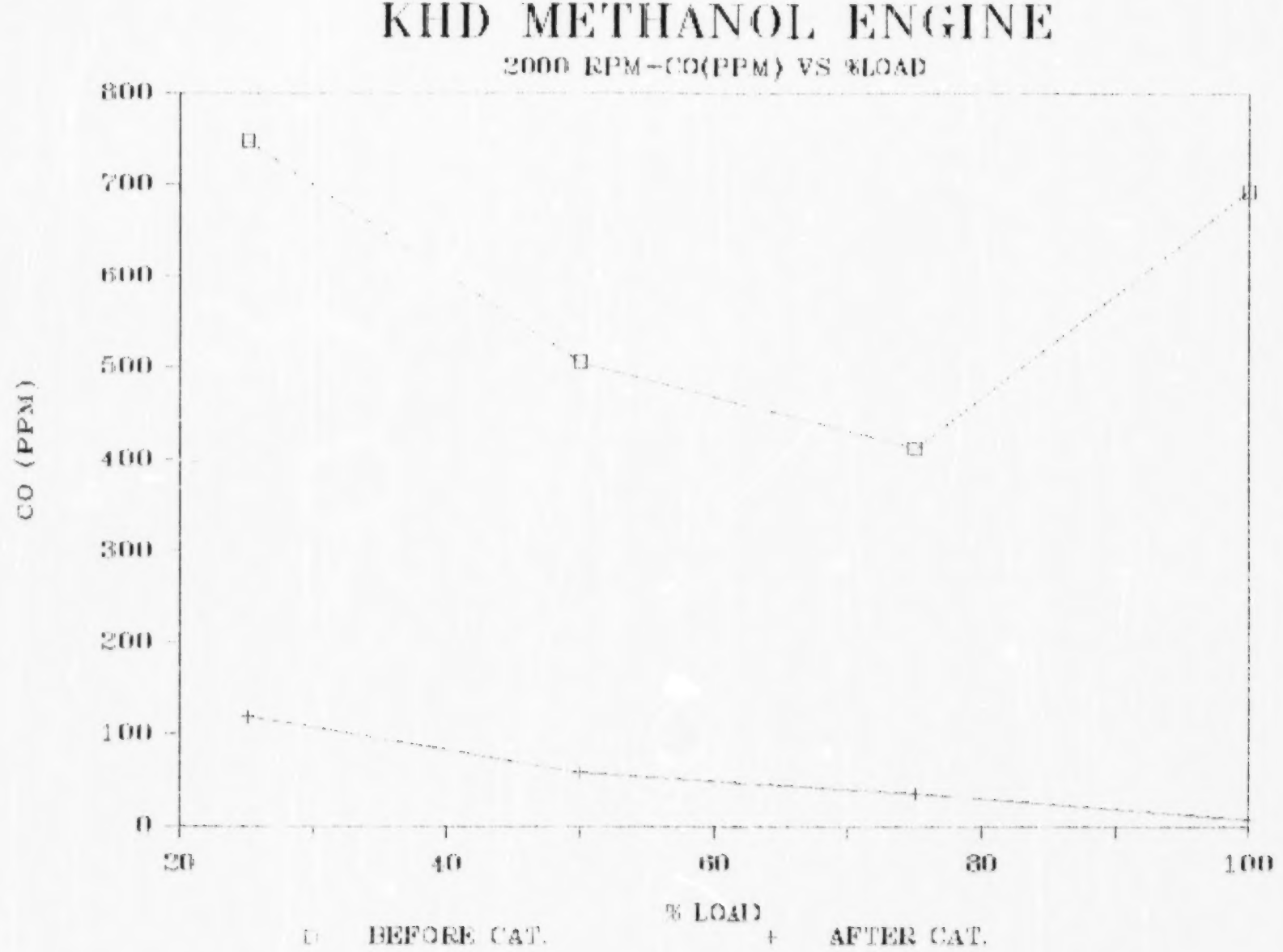

KHD METHANOL ENGINE
2000 RPM-CO(PPM) VS %LOAD
800
700
600
500
400
300
200
100
0
CO (PPM)
20
40
60
80
100
% LOAD
BEFORE CAT.
AFTER CAT.

FIGURE 19

KHD METHANOL ENGINE

2000 RPM – NOX (PPM) VS %LOAD

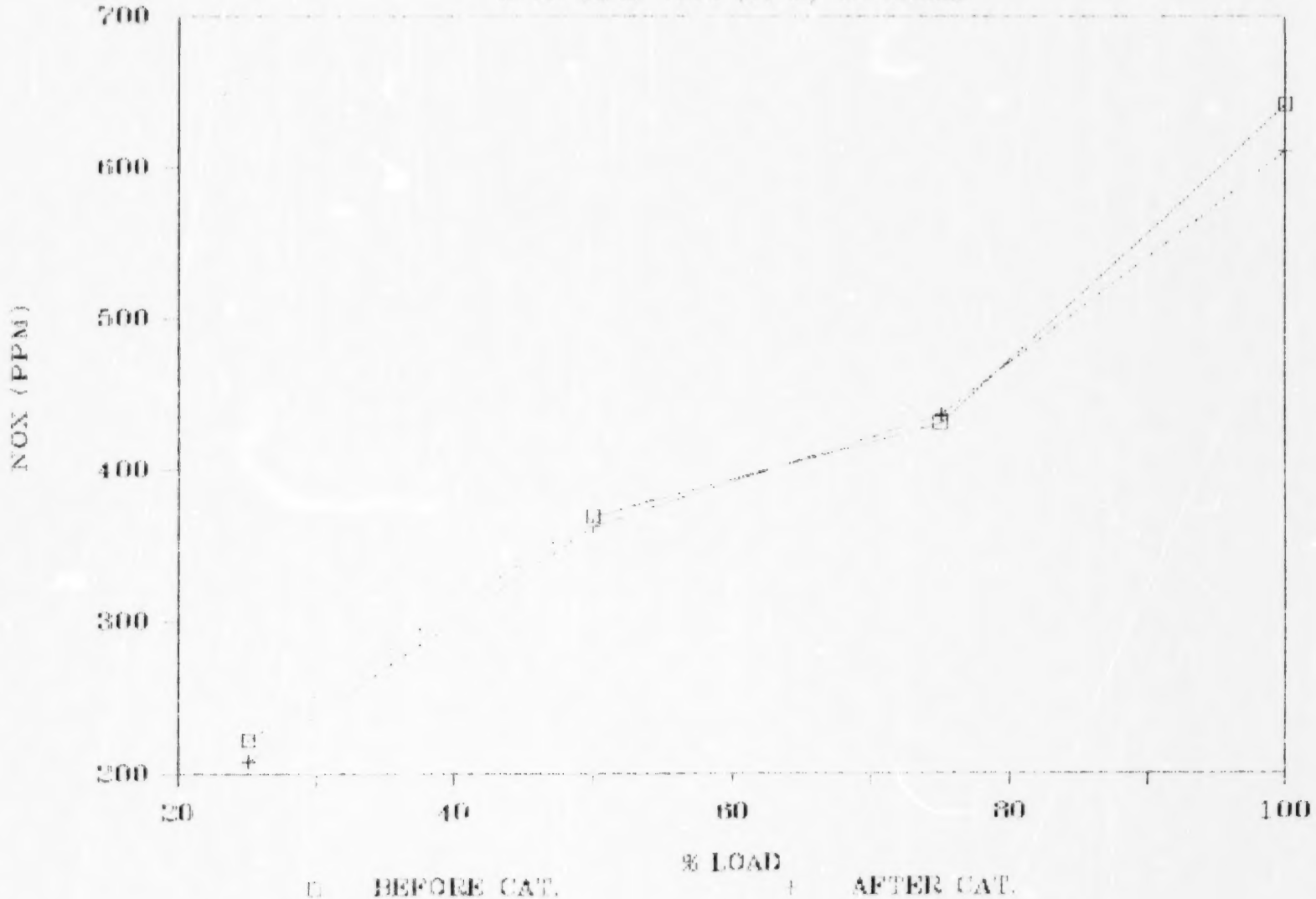


FIGURE 20

KHD METHANOL ENGINE

2000 RPM--NO (PPM) VS %LOAD

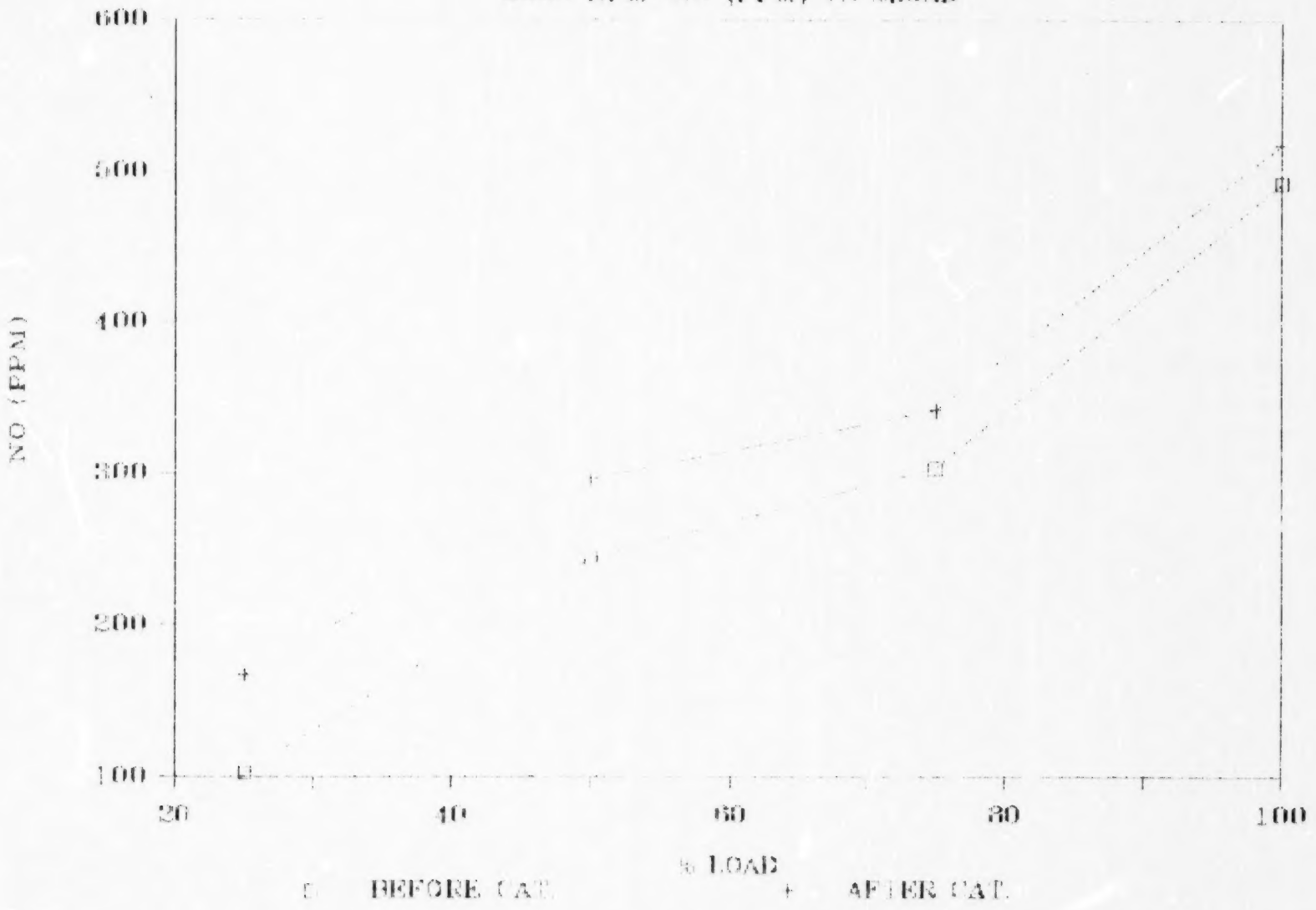


FIGURE 21

KHD METHANOL ENGINE

2000 RPM – NO2 (PPM) VS %LOAD

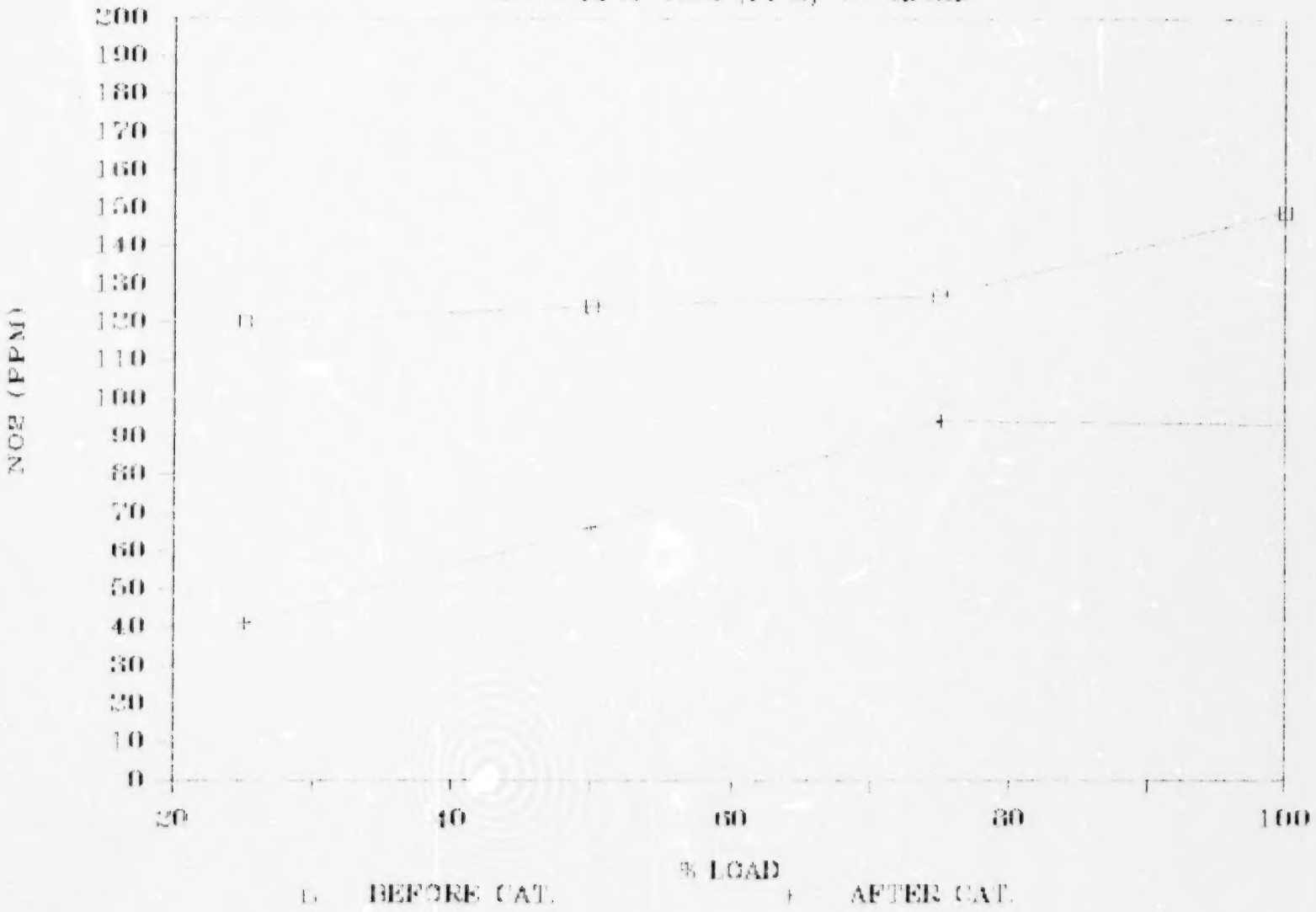


FIGURE 22

KHD METHANOL ENGINE

1500 RPM—%CO2 VS LOAD

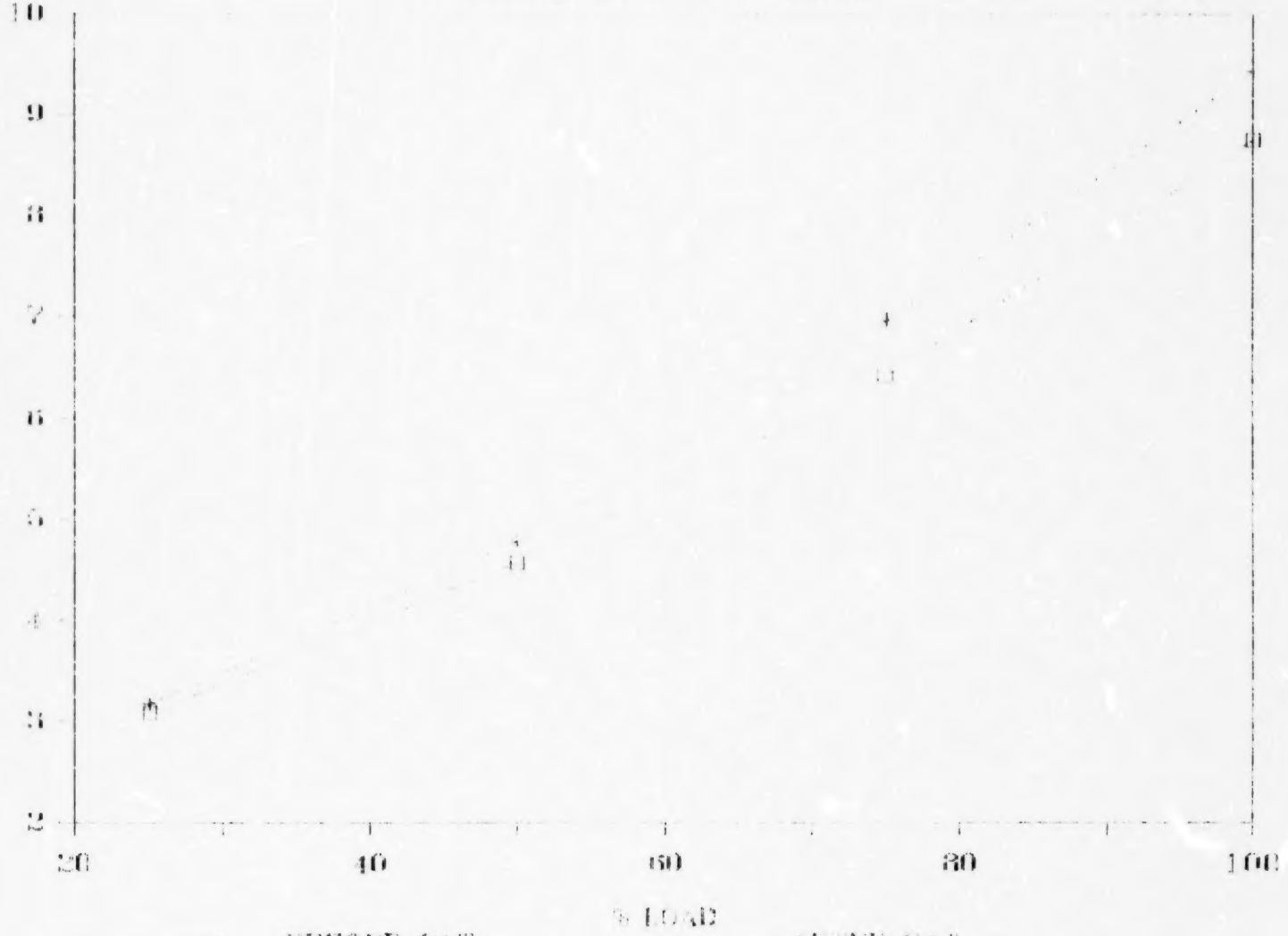


FIGURE 23

KHD METHANOL ENGINE

1500 RPM - THC AS CH_4 (PPM) VS LOAD

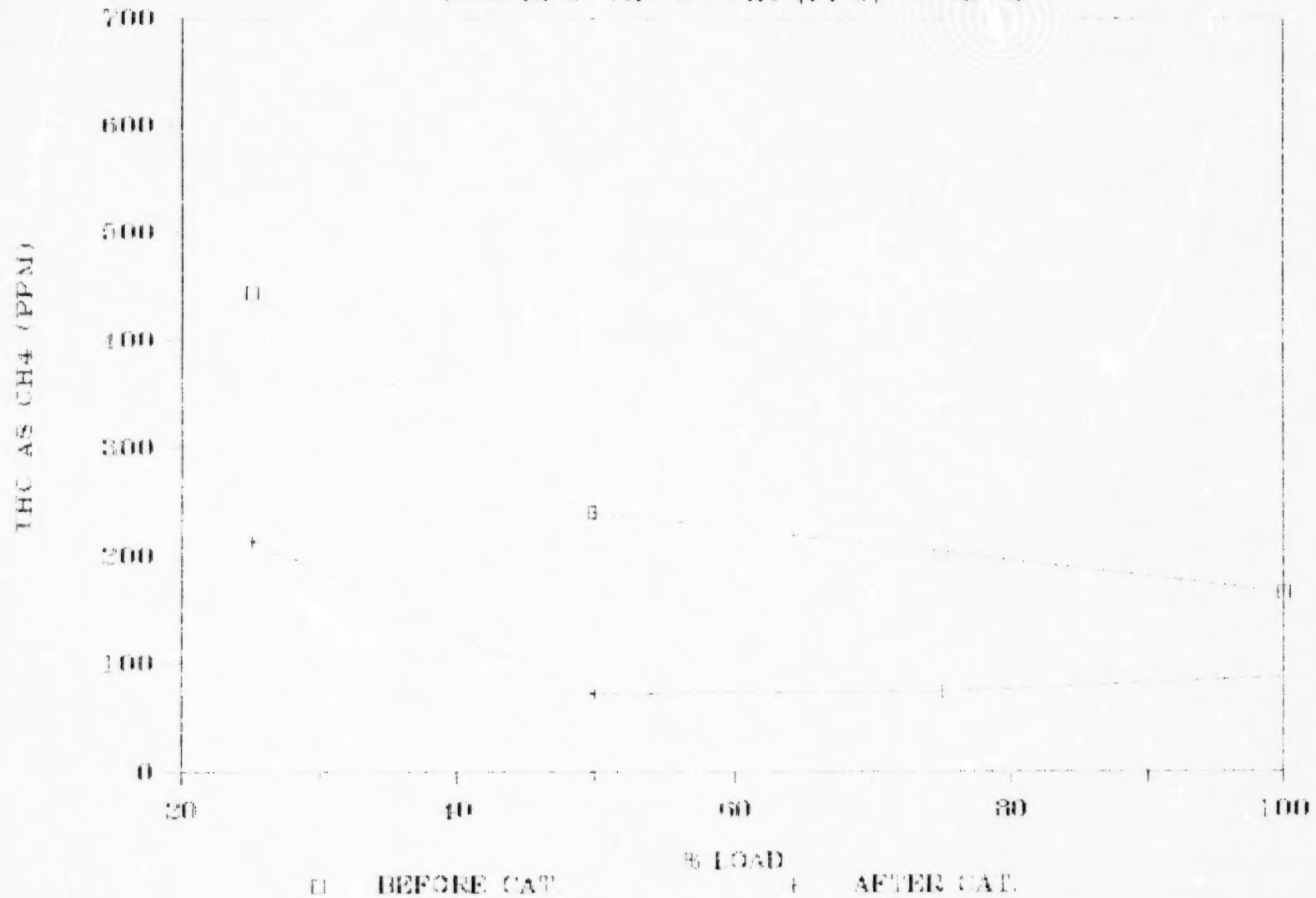


FIGURE 24

KHD METHANOL ENGINE

1500 RPM – CO(PPM) VS %LOAD

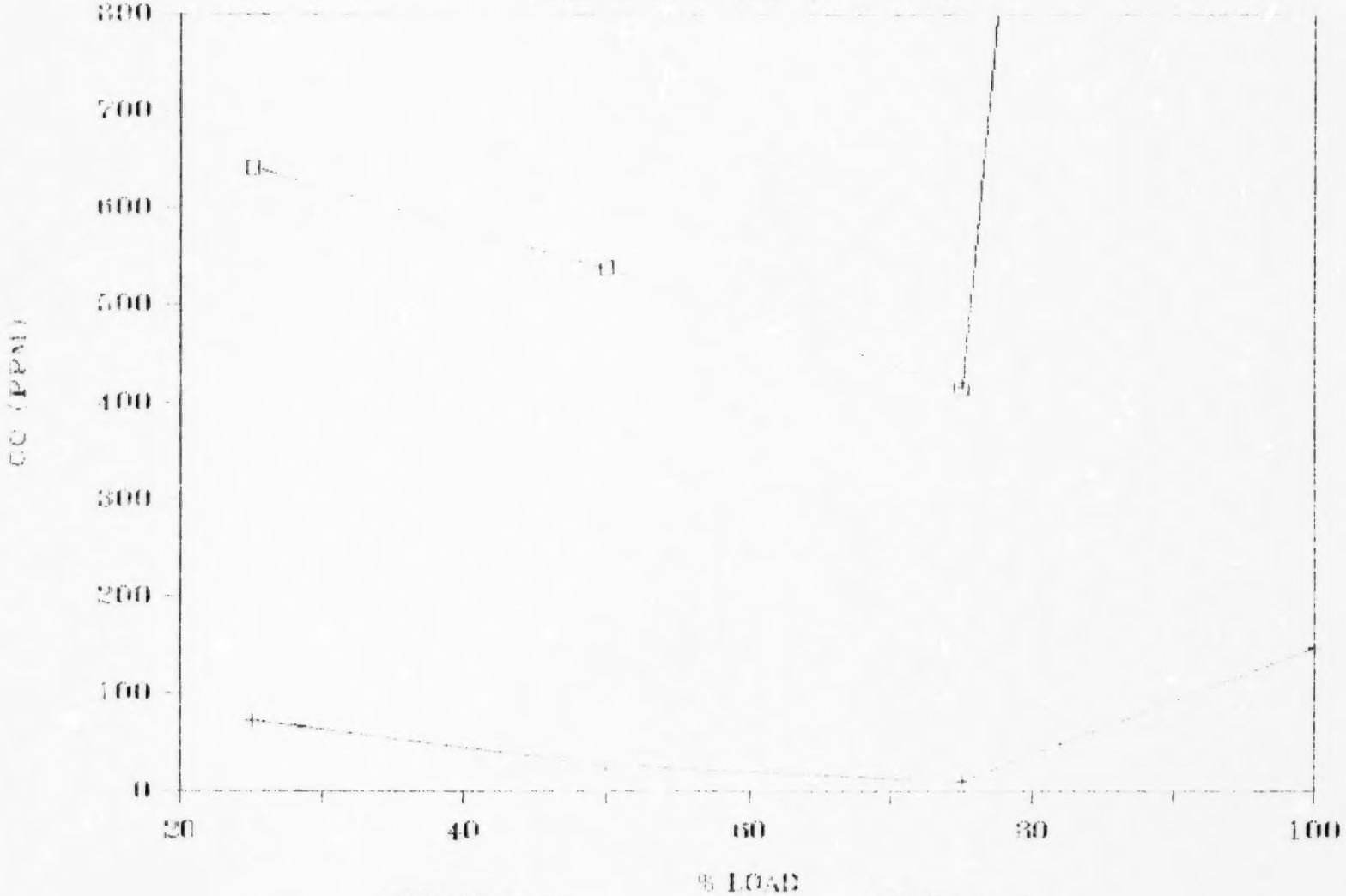


FIGURE 25

KHD METHANOL ENGINE

1500 RPM - NOX (PPM) VS %LOAD

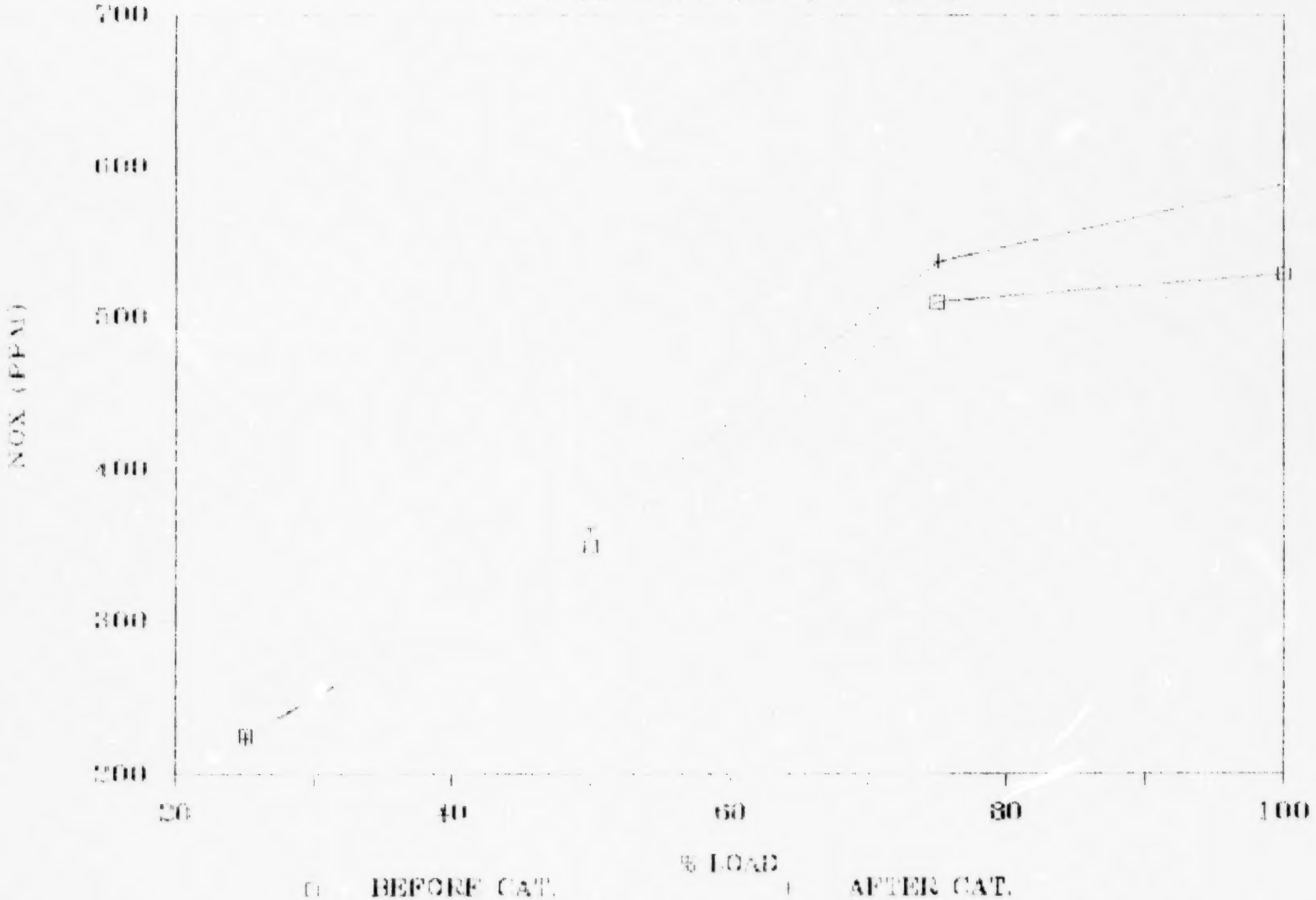


FIGURE 26

KHD METHANOL ENGINE

1500 RPM—NO (PPM) VS %LOAD

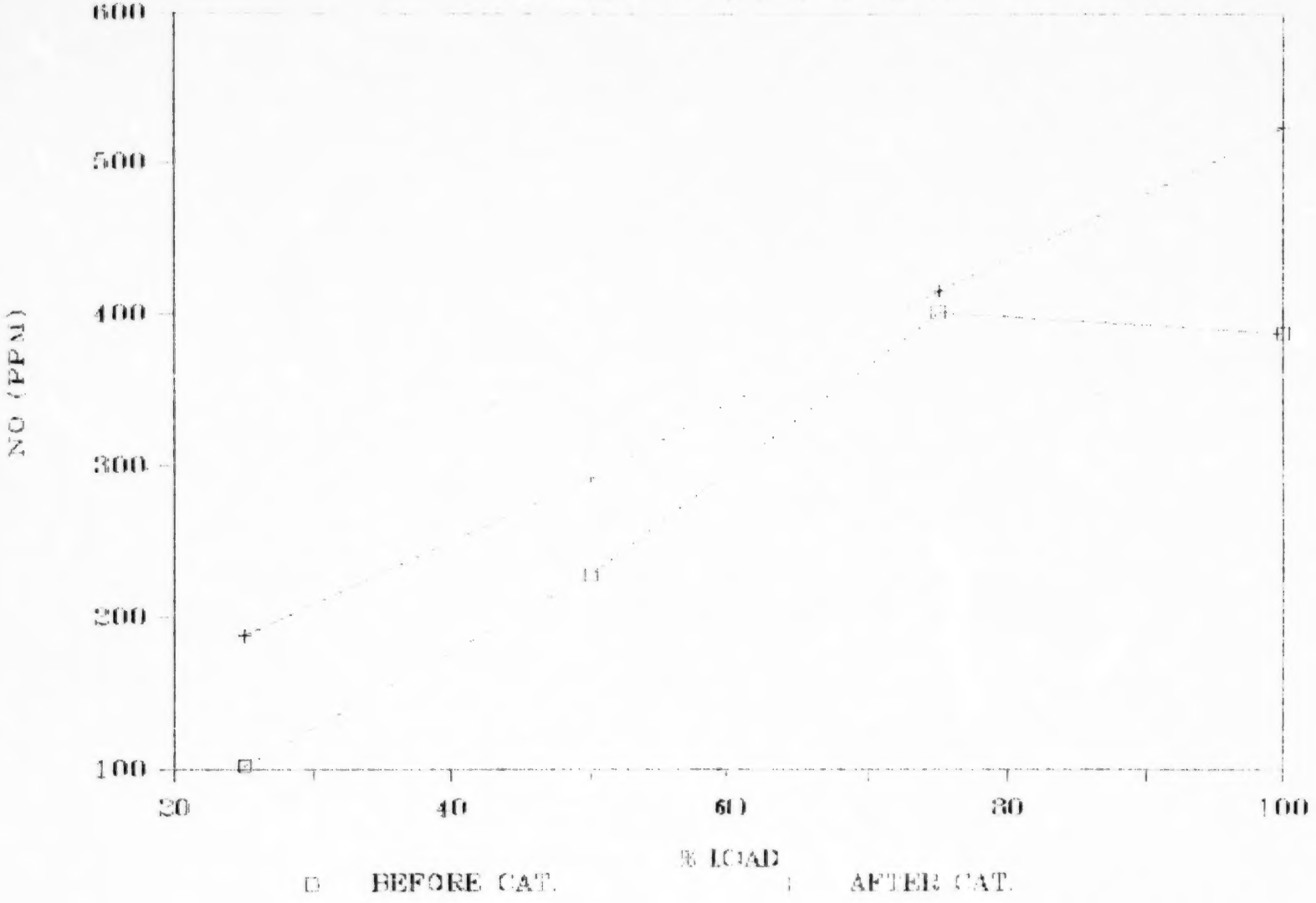
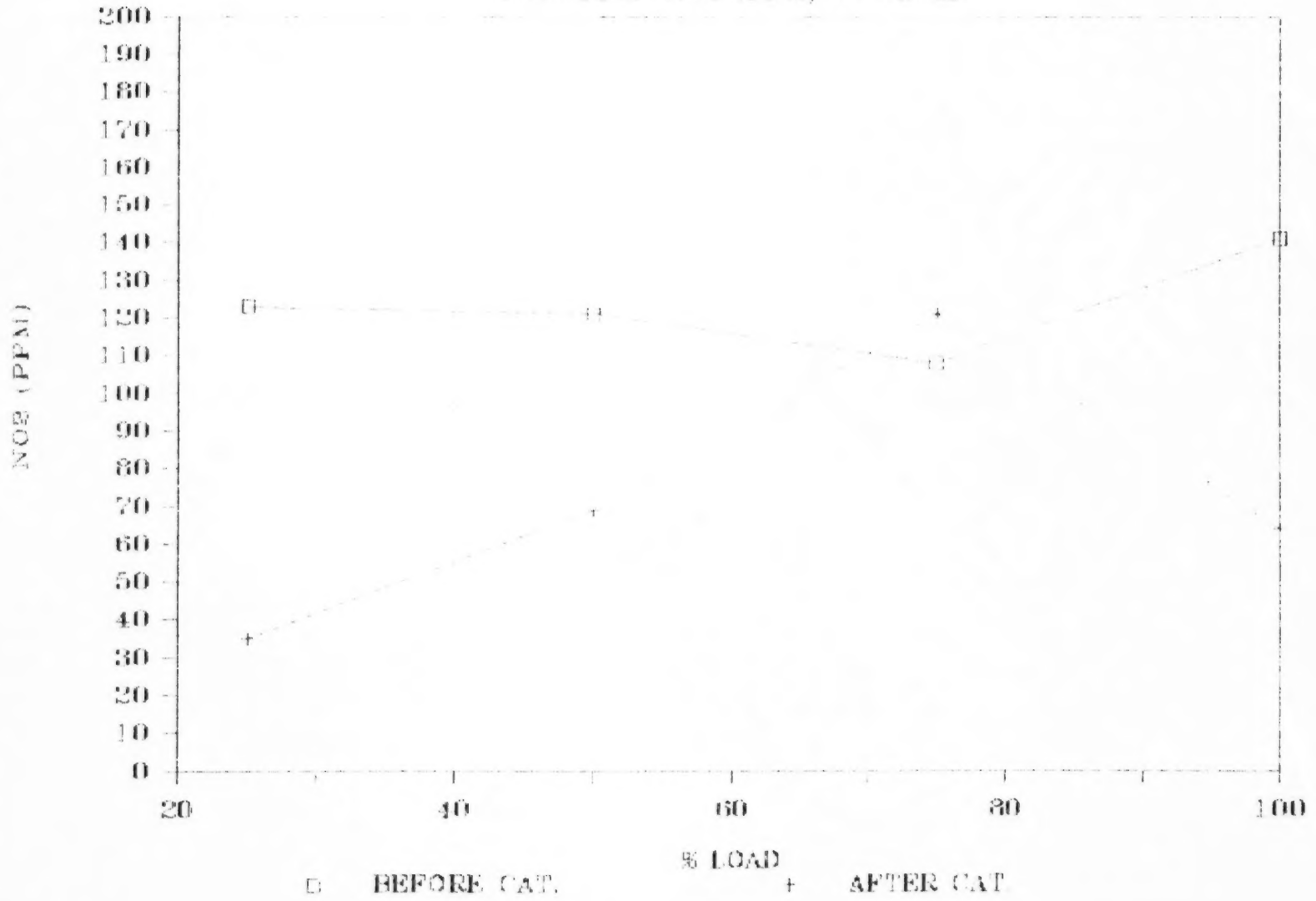


FIGURE 27

KHD METHANOL ENGINE

1500 RPM – NO2 (PPM) VS %LOAD



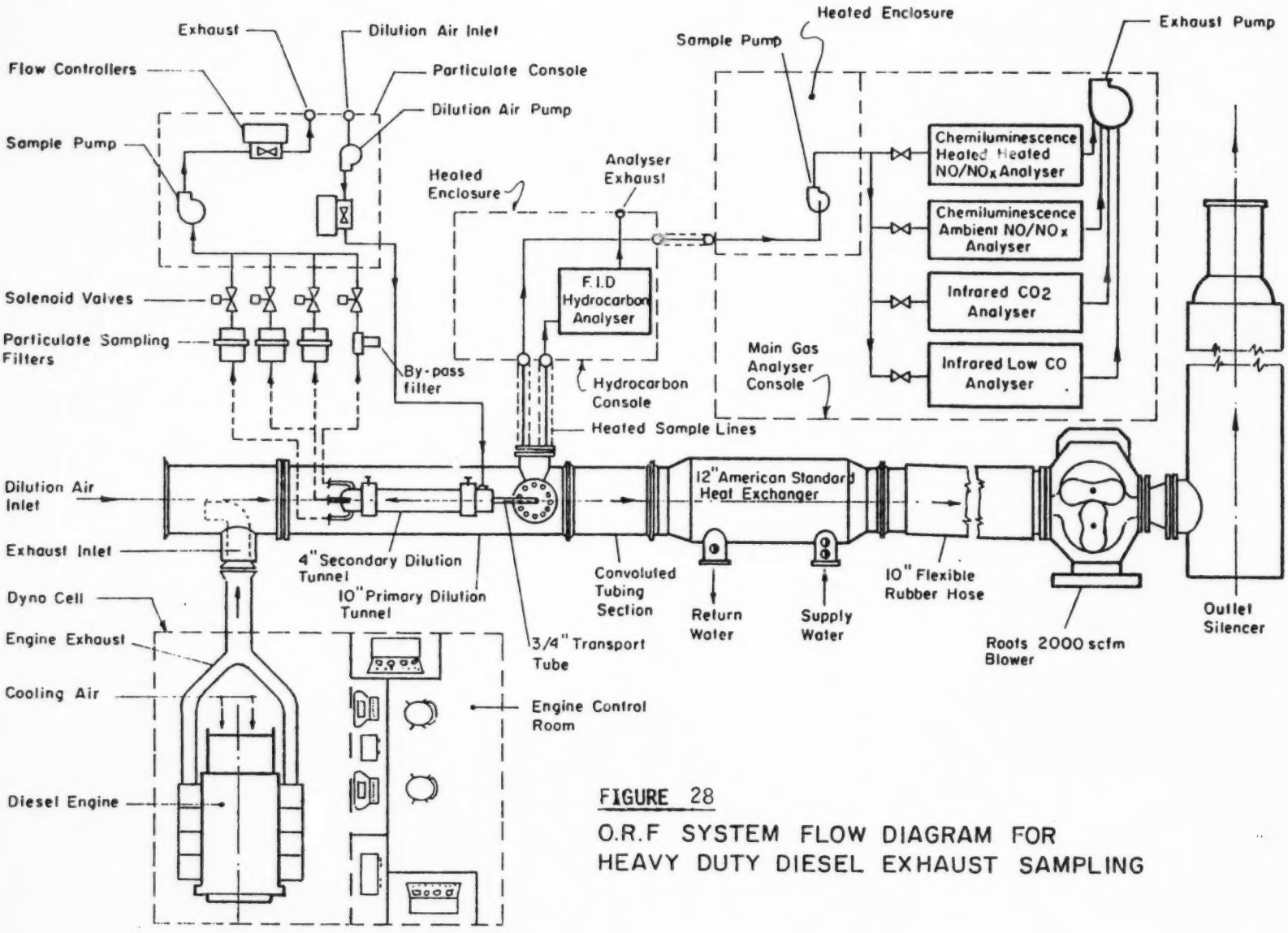


FIGURE 28

O.R.F SYSTEM FLOW DIAGRAM FOR HEAVY DUTY DIESEL EXHAUST SAMPLING

FIGURE 29

KHD METHANOL ENGINE

MTU MOD5 CYCLE

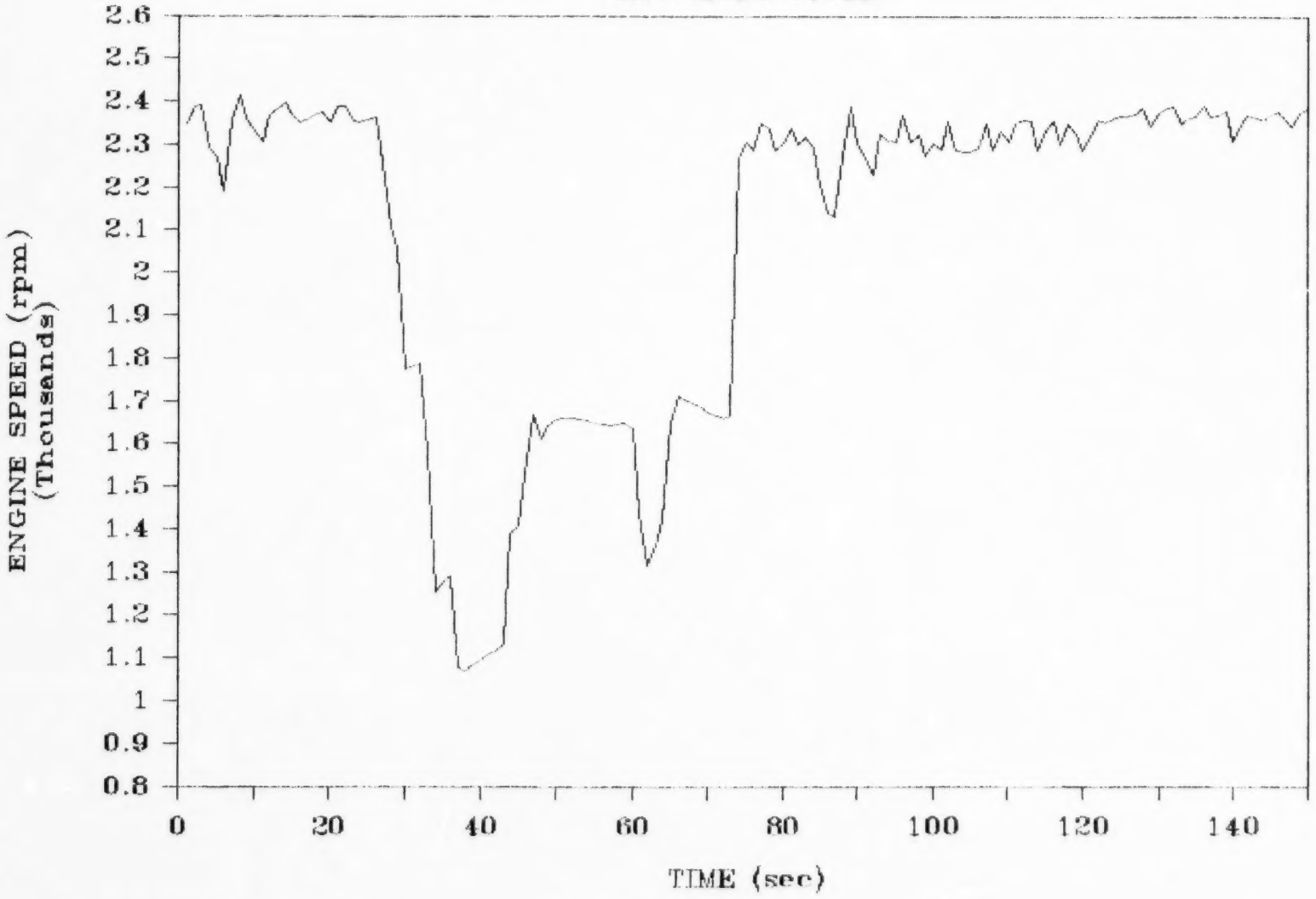
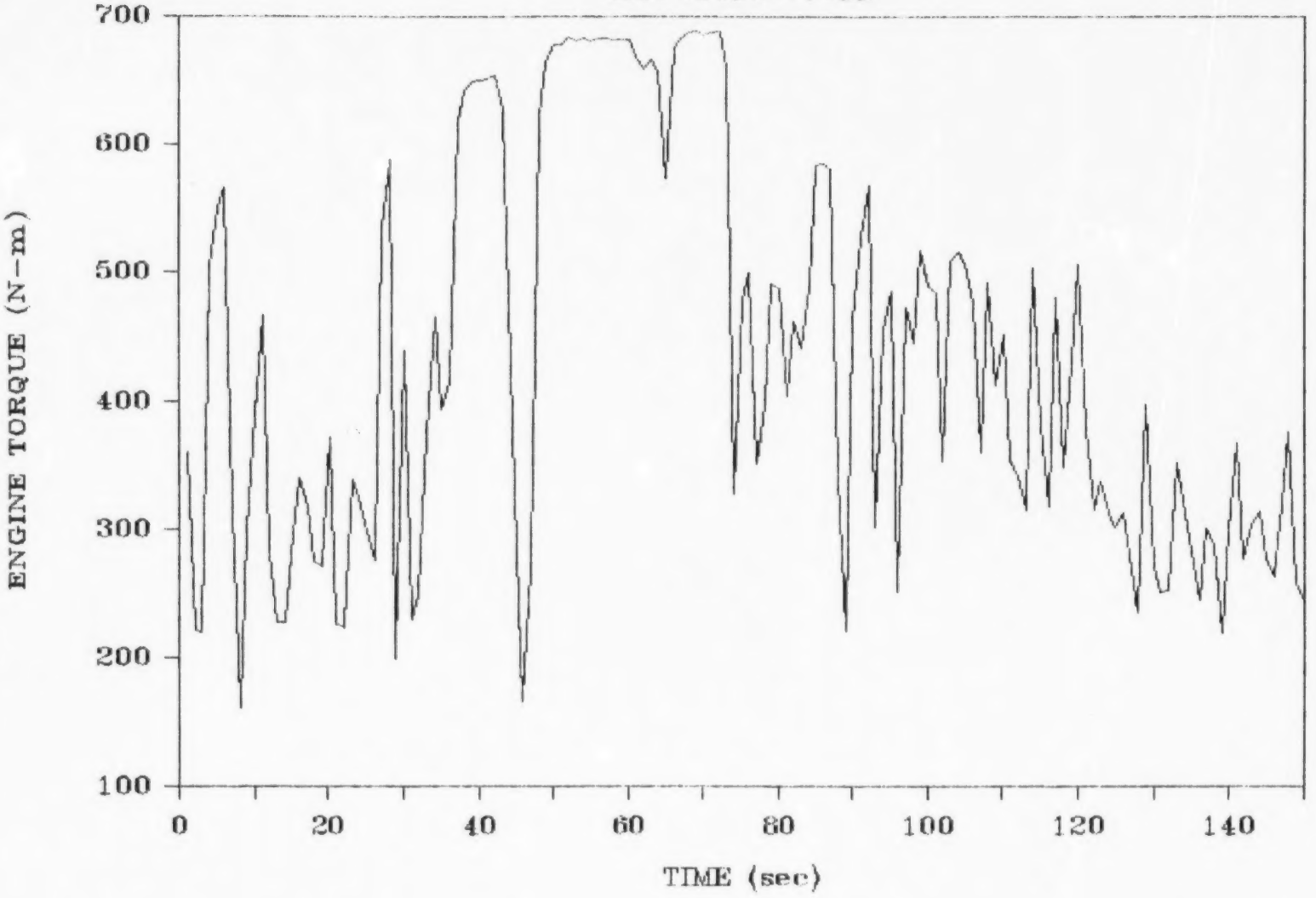


FIGURE 30

KHD METHANOL ENGINE

MTU MOD5 CYCLE



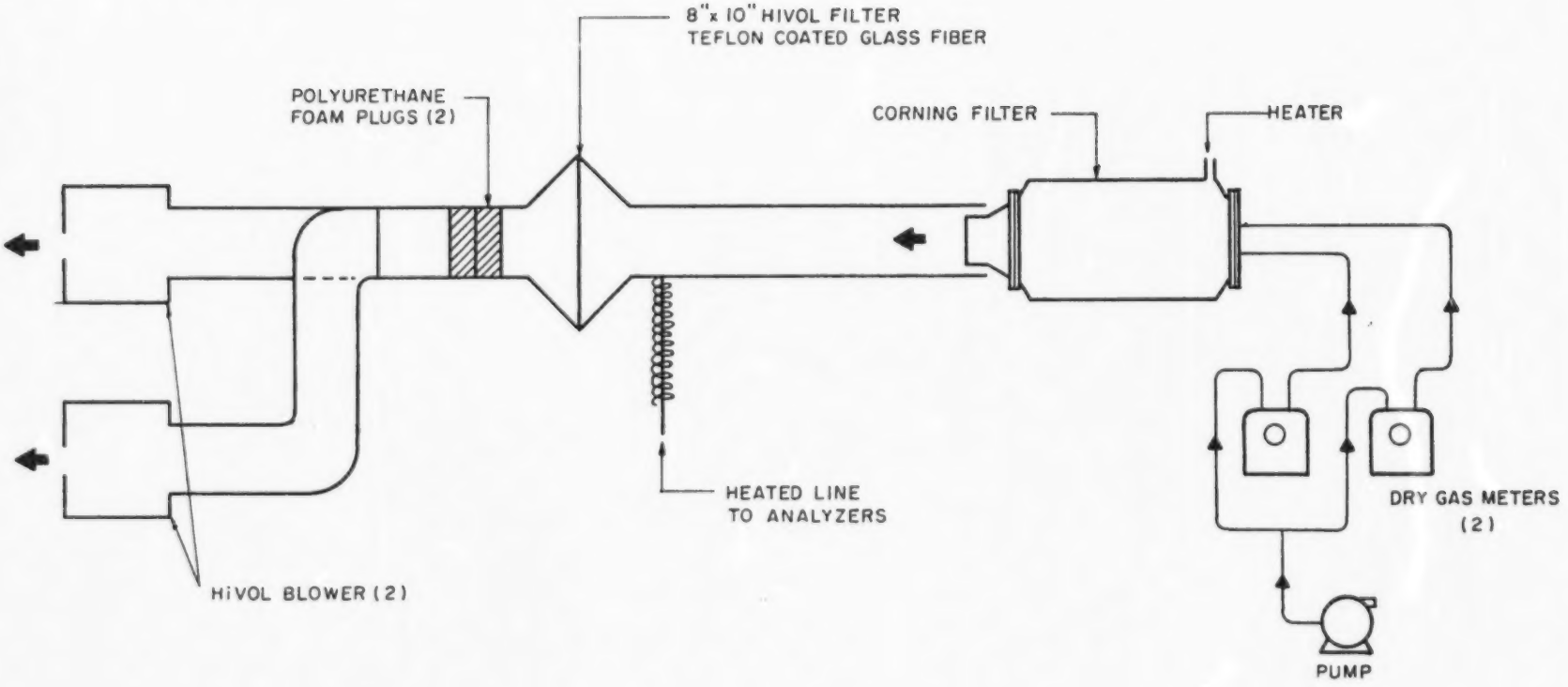


FIGURE 31 MODIFIED DILUTION TUBE SAMPLING SYSTEM SCHEMATIC.

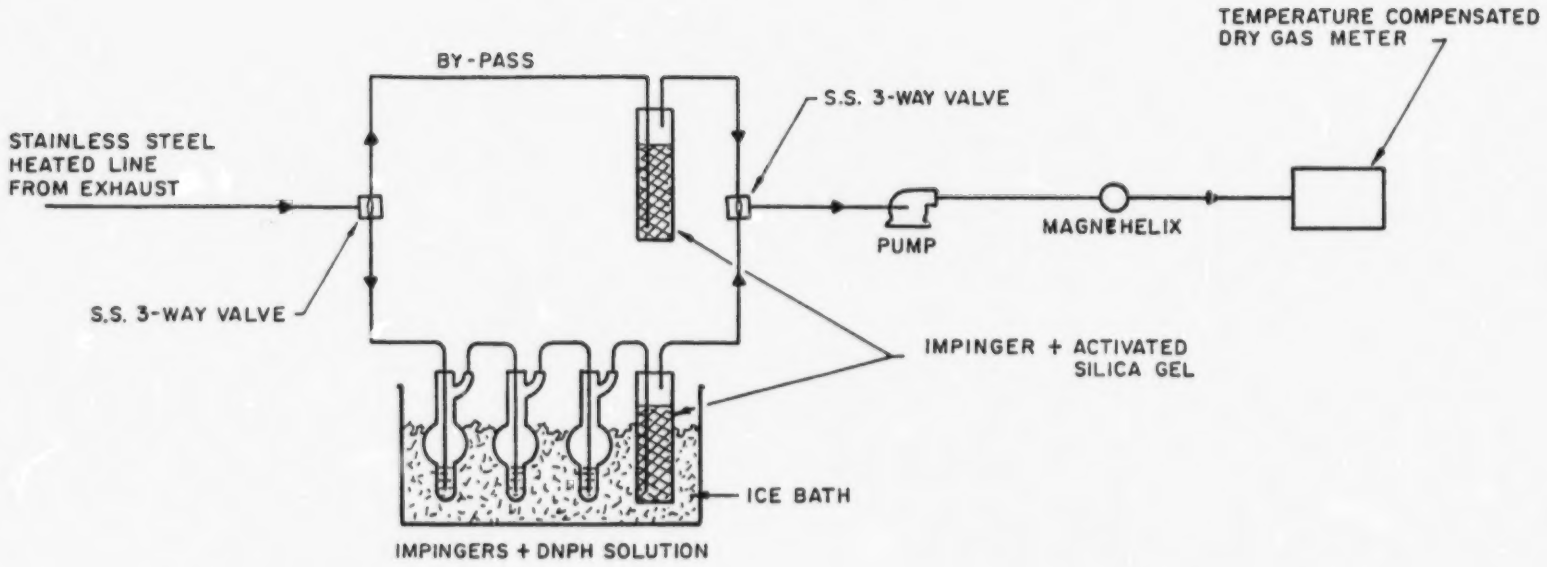


FIGURE 32 Aldehyde and Ketone Sample Collection Flow Diagram

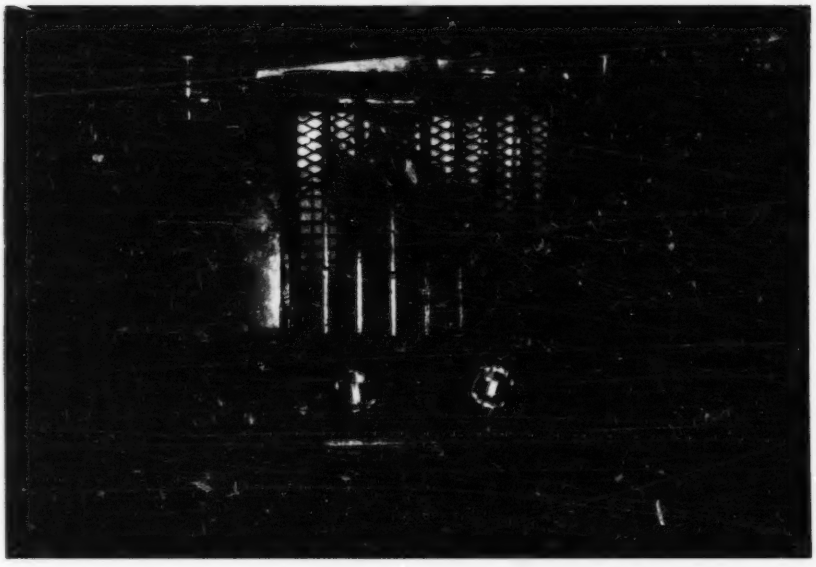


FIGURE 33 - Methanol powered LHD machine.

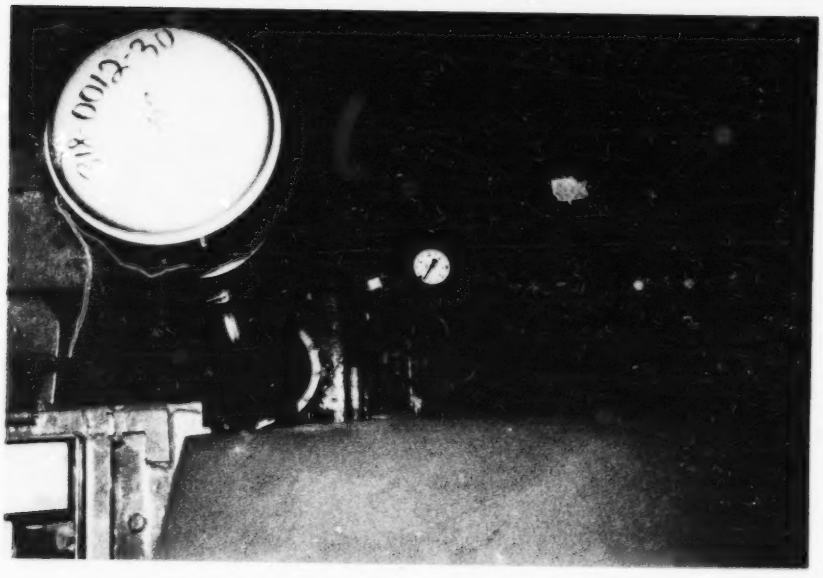


FIGURE 34 - Methanol fuel pump and special 24 V battery hook up.

FIGURE 35 - Methanol Engine in LHD machine showing fuel evaporation system.

FIGURE 36 - Methanol/Pentane Fuel with dye added.